

A MANUAL OF PETROLOGY

F. P. MENNELL



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BY

F. P. MENNELL, F.G.S.

Curator of the Rhodesia Museum, 1901-8,
President of the Rhodesia Scientific
Association, 1910-11.

AUTHOR OF

"An Introduction to Petrology,"
"The Miner's Guide," "The Geology of Southern Rhodesia,"
"The Rhodesian Miner's Handbook," &c.

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Preface

THE present work is founded on *An Introduction to Petrology*, published in 1909. It was originally intended as a third edition of the latter, but the changes which seemed advisable in the treatment of some parts of the subject and in the bringing of others up to date were so extensive that a change of title appears fully justified. Some of the old illustrations have been used, but most are new; tables of analyses, etc., have been inserted and larger type has been employed for the text. The chapters on the origin of the igneous rocks and those dealing with metamorphism have been entirely remodelled, and it is hoped that they will be found less crude than some critics of the former volume not unjustly pronounced them to be. They are the result of over ten years' almost continuous field work in South Africa, which has been set out less comprehensively but with more local detail in the *Geological Magazine*, the *Quarterly Journal of the Geological Society*, and elsewhere. For the most part this book was written at too great a distance from the centres of scientific thought to owe much to outside influence, save as conveyed through books. I have, however, to thank Messrs. Franklin White, H. B. Maufe, and A. E. V. Zealley for access to specimens and literature, and for other information. I am also indebted to Prof. G. A. J. Cole and Dr. C. G. Cullis for several suggestions and corrections. As regards illustrations, figs. 38, 43 and 107 are from photographs of slides lent by Mr. Zealley, figs. 82 and 86 from rocks sent me by Mr. G. W. Card, while fig. 45 was made from one of Mr. J. L. Popham's slides. To the last I am under a special debt of gratitude for taking the photographs from which were made figs. 26, 44, 47, 49, 98 and 104. The few figures which have previously appeared elsewhere have their source indicated underneath each of them. Corrections and suggestions from readers will be gratefully received, and any reasonable enquiries on points connected with

PREFACE

the subject-matter of the volume will be answered, if accompanied by a stamped addressed envelope. The supply of rock sections or photographs of the same, to illustrate special features or structures can in most cases be arranged for. It is the author's earnest desire that the book may be found useful by working geologists generally, as well as by the student for whom the more elementary portions are chiefly intended.

ADDENDA ET CORRIGENDA.

- Page 26, fig 10. *Add Mica plate inserted along ggr.*
,, 70, ,, 41. *For granular read shewing.*
,, 133, ,, 70. *Delete x nicols.*
,, 200, *Note.* *For XI read IX.*
,, 220, l. 26. *For Mayse read Mazoe.*

Contents

CHAPTER		PAGE
I	GENERAL PROPERTIES OF THE ROCK-FORMING MINERALS	I
II	CHARACTERS OF MINERALS IN THIN SECTIONS	6
III	PHENOMENA IN POLARISED LIGHT	16
IV	THE ROCK-FORMING MINERALS : (I) ELEMENTS AND OXIDES	28
V	THE ALUMINOUS SILICATES	38
VI	FERRO-MAGNESIAN MINERALS, ETC.	53
VII	MISCELLANEOUS ACCESSORY AND SECONDARY MINERALS	64
VIII	THE IGNEOUS ROCKS : THEIR CLASSIFICATION, STRUCTURE, ETC.	81
IX	ORIGIN AND VARIATIONS OF THE IGNEOUS ROCKS	101
X	THE ACID IGNEOUS ROCKS	118
XI	THE INTERMEDIATE ROCKS	136
XII	THE BASIC IGNEOUS ROCKS	150
XIII	THE ULTRABASIC IGNEOUS ROCKS	165
XIV	THE SEDIMENTARY ROCKS	174
XV	METAMORPHISM	186
XVI	THERMAL METAMORPHISM	195
XVII	REGIONAL METAMORPHISM	203
XVIII	THE ALTERATION AND WEATHERING OF ROCKS	
XIX	THE CHEMISTRY OF THE ROCKS	225
XX	RADIO-ACTIVITY AND THE ROCKS	235
XXI	COLLECTION AND PREPARATION OF MATERIAL	244

A MANUAL OF PETROLOGY.

CHAPTER I.

General Properties of the Rock-Forming Minerals.

THE essential properties of minerals, as of all crystallised substances, are of two sorts. Firstly, there are those which do not involve any particular direction, but represent the nature of the mineral in the aggregate, and secondly, those which are measured in some definite direction. Hence a distinction may be made between the general properties and directional properties ; to the former belong the density, the specific heat, the temperature of fusion, and the chemical composition ; to the latter the cohesion, the elasticity, and a number of the optical, thermal, electric and magnetic properties, as well as the crystalline form.*

Density and specific gravity are perhaps the most readily determined of the non-directional properties of the minerals with which we have to deal. Owing, however, to the generally small size of the fragments available for its determination, it is often impossible to make use of the methods ordinarily employed. Recourse has to be had to processes applicable to the minute particles constituting a rock powder, and by preference to those which help in the separation of the various constituents.

Heavy liquids furnish a convenient means both of isolating the different minerals of which a rock is composed, and of determining their density. The rock is powdered and reduced to such a fineness that each grain may, as a rule, be taken to consist of a single mineral. Methylene iodide is then diluted with benzole, or a solution of the double iodide of mercury and potassium with water, until

* Miers, *Mineralogy*, London, 1902.

the medium employed has a density intermediate between the supposed constituents of the rock. If correctly adjusted, the heavier minerals will then sink, and the lighter ones will float on the surface of the liquid. Further separations may be made in each case by using a solution of greater or less density. The isolated constituents may then have their specific gravity determined by comparison with mineral fragments of known density. The density of the methylene iodide is 3.3, and that of the concentrated mercury-potassium-iodide (Sonstadt's solution) nearly 3.2 times that of water.

Professor Sollas' *diffusion column* has proved a very useful development of this method of taking specific gravities. Some of the methylene iodide is poured into a test tube and on top of it, say, twice as much benzole. After corking and putting aside for some hours to allow of their diffusing, the two liquids will form a column with its density increasing in proportion as the bottom of the tube is approached. On dropping in the powder of a rock, each grain will sink till it reaches a stratum of its own density, and this may in turn be determined by the use as indicators of substances of known specific gravity.

For determining the specific gravity of rocks, large specimens should be employed, and the best method is undoubtedly to measure the amount of water displaced in a graduated vessel by the carefully weighed specimen.

Magnetic Separation. A useful adjunct in the separation of rock constituents and of mineral residues of various kinds is the electro-magnet,* though its employment has very definite limitations. An ordinary permanent magnet will, of course, extract magnetite from a rock powder, and usually pyrrhotine, as well as some varieties of haematite and ilmenite if it is sufficiently strong. By the aid of adjustable pole-pieces its usefulness can be much extended, though it is never as convenient to use as the electro-magnet.†

* See Crook, *Science Progress*, July, 1907.

† Crook, *Geol. Mag.*, 1908.

TABLE OF SPECIFIC GRAVITIES OF MINERALS.

2.15	Opal	3.18	Fluor
2.16	Graphite	3.18	Andalusite
2.26	Analcime	3.20	Enstatite (up to 3.45)
2.30	Glaucconite	3.20	Apatite
2.30	Tridymite	3.23	Fibrolite
2.30	Sodalite	3.26	Zoisite
2.32	Gypsum	3.30	Augite (varies)
2.32	Nosean	3.30	Chloritoid (Ottrelite)
2.45	Haüyne	3.33	Olivine
2.47	Leucite	3.40	Epidote
2.56	Serpentine	3.40	Idocrase
2.56	Microcline	3.50	Sphene
2.56	Orthoclase	3.52	Diamond
2.60	Nepheline	3.53	Topaz
2.60	Kaolin	3.55	Spinel (up to 4.1)
2.62	Chalcedony	3.62	Kyanite
2.63	Cordierite	3.65	Staurolite
2.64	Albite	3.80	Limonite
2.65	Quartz	3.90	Orthite
2.66	Oligoclase	3.90	Corundum (up to 4.1)
2.68	Andesine	4.03	Perovskite
2.69	Beryl	4.10	Corundum
2.70	Talc	4.10	Spinel (from 3.55)
2.70	Scapolite	4.22	Rutile (up to 5.2)
2.71	Labradorite	4.30	Garnet (from 3.15)
2.72	Calcite	4.45	Chromite
2.72	Chlorite (Pennine)	4.48	Barytes
2.75	Chlorite (Clinocllore)	4.61	Pyrrhotine
2.75	Anorthite	4.69	Zircon
2.85	Dolomite	4.84	Ilmenite
2.85	Wollastonite	5.03	Pyrites
2.90	Biotite	5.10	Haematite
2.90	Muscovite	5.10	Monazite
3.00	Melilite	5.17	Magnetite
3.10	Actinolite	5.20	Rutile (from 4.22)
3.14	Tourmaline	5.20	Haematite
3.15	Hornblende (varies)	6.95	Cassiterite
3.15	Garnet (up to 4.3)	7.55	Iron

Chemical Reactions. The chemical composition of a mineral is its most important feature, but it is seldom necessary to determine the exact composition of a rock-former in order to identify it: in fact, the optical and other constants are now so well known and so characteristic

that they usually suffice of themselves. At the most the presence of some important constituent is sought as a confirmation of the inference from the optical properties. The student is presumed to have a general knowledge of chemical methods, so that we need not refer in detail to them here. The more useful rough tests are indicated under the various minerals in the chapters devoted to their description. It is scarcely necessary to remark that the test must as a rule be applied to fragments carefully isolated from the other minerals of the rock in which they occur by specific gravity methods, or by careful microscopic separation. In certain cases it is possible to obtain reactions from the minerals in an uncovered rock section, but care must be taken to avoid confusion. Such simple tests as solubility or insolubility in acids, gelatinisation, effervescence, etc., are often of great assistance, and their aid should never be neglected. The blowpipe is also very useful at times. The flame colouration, behaviour with fluxes like borax, microcosmic salt, and carbonate of soda, are frequently of service and are usually of easy application; thus magnetite, ilmenite and chromite are readily discriminated after being washed out of a rock powder. If the mineral is soluble in ordinary acids, the usual wet processes may be employed, and if not, valuable indications may be obtained by micro-chemical methods after treatment with hydrofluoric acid on platinum foil.

Silica Percentages. From the mineral constitution of a rock, its probable silica percentage and general chemical constitution can often be determined with considerable closeness. For the calculation of the former it is unnecessary to use any elaborate means, and such methods as weighing dissected micro-photographs often give far less accurate results than estimates made from mere inspection of a rock-slice. Care must, however, be taken not to attach excessive importance to conspicuous minerals and a micrometer arrangement* may be used to advantage. The following table gives some rough average values which may be used in making calculations of this kind, either from mere inspection, or after the employment of one of the methods of separation already referred to :

* See Wade, *Geol. Mag.*, 1907, p. 171.

Approximate Silica Percentages.

Quartz	..	..	..	..	..	100
Albite	..	..	..	..	..	67
Orthoclase and Microcline	..	..	..	..	..	65
Oligoclase	..	..	..	..	..	63
Andesine	..	..	..	..	..	58
Enstatite	..	..	..	..	..	55
Leucite	..	..	..	..	..	55
Augite	..	..	..	..	..	50
Labradorite	..	..	..	..	..	50
Hornblende	..	..	..	..	..	45
Anorthite and Nepheline	..	..	..	..	..	45
Muscovite	..	..	..	..	..	45
Olivine and Melilite	..	..	..	..	..	40
Biotite	..	..	..	..	..	35
Sphene	..	..	..	..	..	30
Apatite, Magnetite and Ilmenite	..	..	..	..	..	0

CHAPTER II.

Characters of Minerals in Thin Sections.

Crystalline Form. Like other minerals, the rock-formers are capable for the most part of assuming definite crystalline form. This may not be developed as far as actual outline is concerned, but the molecular structure of which crystallisation is the outward evidence is none the less perfect on that account, and by means of the optical and other phenomena to which it gives rise it is generally possible to determine the system of crystallisation and the identity of the mineral itself. The following table gives a list of the minerals described in this work, arranged according to their respective systems of crystallisation.

TABLE OF CRYSTALLINE FORMS.

<i>Regular.</i>	<i>Tetragonal.</i>	<i>Hexagonal.</i>	<i>Rhombic.</i>	<i>Monoclinic.</i>	<i>Anorthic.</i>
Diamond	Rutile	Graphite?	Andalusite	Orthoclase	Microcline
Iron	Cassiterite	Quartz	Staurolite	Muscovite	Albite
Spinel	Melilite	Chalcedony?	Enstatite	Biotite	Oligoclase
Chromite	Scapolite	Corundum	Olivine	Hornblende	Andesine
Magnetite	Zircon	Haematite	Cordierite	Augite	Labradolite
Leucite	Copper	Ilmenite	Topaz	Sphene	
Haüyne	Pyrites	Nepheline	Talc	Orthite	Bytownite
Sodalite	Idocrase	Apatite	Chlorite	Kaolin?	Anorthite
Perovskite		Beryl	Zoisite	Chloritoid	Kyanite
Pyrites		Pyrrhotine	Serpentine	Epidote	
Fluor		Tourmaline		Gypsum	
Garnet		Calcite		Wollastonite	
		Dolomite			

Cleavage. Crystal outline is seldom seen in great perfection among the constituents of an ordinary rock, and moreover, in sections cut at haphazard, such as is the case with ordinary rock slices, the form may be very difficult to recognise from the shape of the section shown. When the mineral does not show definite faces, however, it may be traversed by *cleavage* cracks, which indicate lines of weakness determined by the crystalline structure. These cracks are at once distinguished from the irregular lines of fracture which traverse such minerals as quartz, by

their straightness and parallelism, and, when there is more than one set, by their intersecting at a constant angle. The cleavages are termed cubic, prismatic, basal, pinacoidal, etc., according to the faces to which they are, or would be, parallel; and in the cases of minerals like augite, hornblende, etc., they are of great diagnostic value in the absence of external crystalline form. The lack of cleavage traces is also characteristic of certain minerals: thus, quartz and olivine may often be distinguished by their lack of cleavage from feldspar and augite respectively, which latter minerals usually show it in considerable perfection. The appended table gives a list of rock formers arranged according to the nature of their cleavage.

TABLE OF CLEAVAGES.

<i>Basal.</i>	<i>Prismatic.</i>	<i>Rhombohedral.</i>
(Transverse in longitudinal sections.)	(Parallel to both edges in transverse, and to long edge in vertical sections.)	(Two intersecting cleavages in every section.)
Nepheline	Nepheline (120°)	Corundum
*Melilite	Rutile (90°)	Ilmenite
Staurolite	Scapolite (90°)	Calcite
Kyanite	Andalusite (91°)	Dolomite
*Muscovite	Staurolite (130°)	
*Biotite	Hornblende (124°)	<i>Pinacoidal.</i>
Apatite	Augite (87°)	Feldspars
Topaz	Enstatite (92°)	Fibrolite
Beryl	Idocrase (90°)	Staurolite
*Talc		Kyanite
*Chlorite		Wollastonite
*Chloritoid		Gypsum
*Epidote		†Enstatite
Feldspars		Zoisite

Show no definite cleavage as a rule: Quartz, Chalcedony, Spinel, Magnetite, Cassiterite, Leucite, Olivine, Tourmaline, Perovskite, Orthite, Zircon, Cordierite, Pyrites, Sphene, Pyrrhotine, Kaolin, Serpentine, Garnet, Fluor.

* Usually elongated parallel to this direction.

† Sometimes.

Incipient Growths. Besides those cases where crystalline form is imperfectly developed owing to disturbing influences, we sometimes find incipient forms of growth,

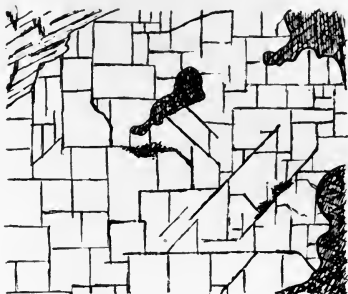


FIG. 1.—PRISMATIC CLEAVAGE OF SCAPOLITE, as seen in basal section, Wallaroo, South Australia. $\times 60$ diam.

due to arrested or irregular development from some such cause as viscosity, due to cooling, or exhaustion of material, and even instances where a drawing together of material has taken place without actual crystallisation. We find, in fact, in certain glassy lavas and dykes, *crystallites*,* due, seemingly, to the aggregation of molecules without



FIG. 2.—CRYSTALLITES: Globulites, Margarites, Belonites, Trichites.

polarity. These are not true crystals, for they do not react on polarised light, and they may, perhaps, be regarded as parts of the magmatic solution, saturated or supersaturated with a particular substance. They sometimes assume definite and peculiar shapes, and special

* This is a somewhat unfortunately chosen name, and considerable confusion has been caused by its use as synonymous with skeleton crystal.

names have been given to some of these, such as the long, hair-like *trichites*, the spherical *globulites*, and the rod-like *belonites* and *longulites*. Very minute crystals are termed microlites. These, of course, react on polarised light, but they sometimes exhibit arrested growth, as far as outline is concerned, forming *skeleton-crystals*, instead of being bounded by plane faces. Thus sections of felspar and augite often have forked terminations, and when cut



FIG. 3.—PLAGIOCLASE, in glassy Enstatite Rhyolite, New Zealand. $\times 50$ diam.



FIG. 4.—AUGITE in Dolerite, Bulawayo, Rhodesia. $\times 90$ diam.

SKELETON CRYSTALS.

transversely, show an infilling of groundmass. Quartz, and sometimes augite, form little hooks; hornblende and magnetite shew fern-like and arborescent forms, and so on.

Colour. When rocks are reduced to the thinness of an ordinary section, few of their constituents remain completely opaque, and even those which are very dark coloured megascopically, often show little or no colouring under the microscope. The possession of a marked tint

accordingly becomes of considerable assistance in determining the nature of the mineral. The following table shows the principal rock-forming minerals, grouped according to their behaviour in respect to colour and transparency :—

OPAQUE.	COLOURED. (in most cases).	COLOURLESS. (or very faintly coloured).
Chromite*	Biotite	Andalusite
Copper pyrites	Cassiterite	Apatite
Graphite	Chlorite*	Augite*
Haematite*	Chloritoid*	Beryl
Ilmenite	Corundum*	Calcite
Iron	Enstatite*	Chalcedony
Kaolin*	Epidote*	Cordierite
Magnetite	Fluor*	Diamond
Pyrites	Hauyne	Dolomite
Pyrrhotine	Hornblende	Felspars
	Idocrase	Fibrolite
	Orthite	Garnet*
	Perovskite	Gypsum
	Rutile	Kyanite*
	Serpentine*	Leucite
	Sodalite*	Melilite
	Sphene*	Muscovite
	Spinel*	Nepheline
	Staurolite*	Olivine
	Tourmaline	Quartz
		Scapolite
		Talc
		Topaz
		Wollastonite
		Zircon*
		Zoisite

In the above table a * against a mineral in the first column denotes that it may, in rare instances, become transparent. In the second column it denotes that the colour may be very faint, or even imperceptible, in certain occurrences, while in the third it indicates that occasionally the mineral is more or less strongly coloured.

It will be noted that the great majority of the minerals here dealt with become transparent in sections. Those which do not may be fairly readily detected by attention

to the points enumerated in the subjoined table. It may be further pointed out that most of them are heavy, and may therefore be separated from a rock powder by some process of concentration, and tested by the blow-pipe or other means.

CHARACTERISTICS OF OPAQUE MINERALS.

MINERAL.	FORM.	COLOUR IN REFLECTED LIGHT	DECOMPOSITION PRODUCTS
<i>Chromite</i>	Granules	Dead black. Grey and not quite opaque in very thin sections	Brownish or reddish
<i>Copper Pyrites</i>	Irregular	metallic yellow	Greenish and brownish
<i>Graphite</i>	Flakes & Patches	Dead black	None as a rule
<i>Haematite</i>	Irregular	Dull red to metallic purplish or black. Not quite opaque (red) in very thin sections	Brownish
<i>Ilmenite</i>	Skeleton crystals, or irregular grains	Dead to shining black	White or grey
<i>Iron</i>	Irregular	Metallic grey	Brownish or reddish
<i>Kaolin</i>	Cloudy aggregates	Dull white	(In felspar)
<i>Magnetite</i>	Crystals or grains	Shining black	Brownish or reddish
<i>Pyrites</i>	Crystals or grains	Pale metallic yellow	Do.
<i>Pyrrhotine</i>	Irregular	Bronze	Do.
<i>Sphene (leucocoxene)</i>	Irregular	Dull dirty white	(With ilmenite)

NOTE.—Iron and Magnetite are strongly magnetic. Pyrrhotine slightly so.

When a coloured mineral is pleochroic, *i.e.*, varies in colour according to the direction in which light passes through it, the *pleochroism* furnishes an important diagnostic character. Even in quite faintly coloured minerals, pleochroism may often be readily detected, while in some colourless minerals the absorption of light may vary greatly according to its direction, so that a section becomes noticeably less illuminated in certain positions.

In ordinary crystals pleochroism may be observed by merely holding them up to the light first one way and then another, but the tints shown are merely face colours and are mixtures of the pure axial colours which may be observed in sections. This is usually done by rotating

the slice on the stage of the microscope with the polariser in position but with the analyser removed. The greatest variations are observed in positions at right angles to one another, these being the positions of extinction (see after) and corresponding with the directions of the axes of optical elasticity. Minerals of the cubic system cannot show pleochroism, as they affect light equally in all directions, and it must also be borne in mind that basal sections of tetragonal and hexagonal minerals likewise show no change on rotation. In longitudinal sections, however, the minerals of those systems exhibit the colour of the extraordinary ray, E, when the principal axis is placed parallel to the principal section (*i.e.*, the shorter diagonal) of the lower nicol. At 90° from that position the crystal will exhibit the colour of the ordinary ray, O. The scheme of pleochroism may accordingly be set down shortly in this fashion: For tourmaline O=blue, E=colourless.

In the so-called biaxial minerals there are often three distinct colours in the directions of the three axes of optical elasticity. Longitudinal sections showing the maximum extinction angles will give two of these directions, and cross sections also two, one, of course, being common to both sections. In each case, first one direction of extinction and then the other is brought into a position coinciding with the shorter diagonal of the nicol: these will give in turn the axial colours for the two axes to which the section is parallel. The scheme of pleochroism is accordingly indicated as follows: For hornblende α =greenish yellow, β =yellowish green, γ =greenish blue, in certain granites.

The following table roughly indicates the degree of pleochroism of some of the more important minerals, though it must be remembered that this property is subject to a certain amount of variation. Thus it sometimes happens that when a mineral which is usually pale, is in a particular instance abnormally coloured, it is also intensely pleochroic. Abnormal pleochroism may also be seen round inclusions of other minerals (see page 54.) Certain of the minerals which are not mentioned on account of their being colourless in rock slices may be markedly pleochroic in thicker sections, *e.g.*, andalusite:

<i>Strongly Pleochroic.</i>	<i>Feebly Pleochroic.</i>	<i>Not Pleochroic.</i>
Biotite	Chlorite (some vars.)	Cassiterite
Chloritoid (some vars.)	Corundum	Augite (most vars.)
Enstatite (ferriferous)	Rutile	Serpentine
Hornblende	Enstatite (some vars.)	
Epidote	Idocrase	
Kyanite (blue var.)	Orthite (most vars.)	
Tourmaline	Sphene	
Ægirine	Staurolite	

The refractive power of a mineral is another property which may afford a valuable clue to its identity. It will be observed that certain minerals, *e.g.*, quartz, when mounted in Canada Balsam, are practically invisible in ordinary light, their surface appearing perfectly smooth and their edges quite inconspicuous. When embedded in



FIG. 5.—GARNET, IN GNEISS, showing the dark margins and pitted appearance due to a high refractive index, and the inclusions characteristic of metamorphic rocks. Near Limpopo River, Transvaal. $\times 20$ diam.

the coloured ground mass of a rock, they may look exactly like holes rather than porphyritic crystals. Others, like olivine or garnet, seem to stand out in relief, and their edges are very distinct, often looking as if a black line had been drawn round them, while their surface appears wrinkled, or rough and pitted. These phenomena depend on the difference between the *refractive index* of the mineral and the medium in which it is mounted. The more widely the index of refraction departs from that of the Canada balsam, the more striking the phenomena will be, and in the case of minerals like rutile, with extremely high refractive indices, the dark margins are so broad that small

crystals appear to be almost or quite opaque. On the other hand, minerals like quartz and felspar, whose indices of refraction are almost identical with that of Canada balsam, look, as already stated, perfectly smooth and without prominent margins. The relative refractive indices of the two adjacent minerals in a rock slice, or of a mineral and Canada balsam, may be very simply determined by Becke's method, the only condition being perfect contact between the substances in question. On examining the doubtful mineral with a low power, it will be observed that a fringe of white light passes inside or outside its boundary as the focus is altered. When the objective is raised, the band comes inside the more refractive mineral: when it is lowered, inside the less refractive. Hence, for example, it is often possible to determine the species of a felspar by comparing its refractive index with that of Canada balsam or of quartz. A felspar with a higher refractive index than quartz must be at least as basic as andesine. Canada balsam has nearly the same refractive power as quartz.

Zoning.—Before passing on, it may be well to note that crystals are not always of theoretically uniform composition throughout. This may result from changes in their rate of growth or to alterations in the composition of their mother-liquor. The influence of such circumstances may be rendered evident by variations of colour and pleochroism, or of relief, or may require to be brought out by the employment of polarised light, when the double refraction or extinction angle may reveal it (see next chapter). The variations may be quite irregular, but more usually produce successive shells or zones of material quite distinct from each other, or give rise to a gradual change of properties from centre to margin of a crystal. Both these types of zonal structure are well seen in the felspars. Another type of zoning is sometimes seen which appears to depend on interruptions of growth, namely, that due to the presence of regularly distributed inclusions or cavities. The last occasionally take the form of *negative crystals*, having the external shape of their host.

REFRACTIVE INDEX.

The following table gives a list of the minerals referred to in this work, arranged according to their mean refractive index :

<i>Extremely High.</i>			Actinolite	1.63
Rutile	2.76		Melilite	1.63
Diamond	2.42		Dolomite	1.62
Perovskite . . .	2.38		Topaz	1.62
Chromite	2.09		Calcite	1.60
Cassiterite . . .	2.03		<i>Low.</i>	
Zircon	1.99		Biotite	1.59
Hæmatite	1.90		Muscovite	1.58
Sphene	1.90		Beryl	1.58
<i>Very High.</i>			Scapolite	1.58
Garnet	1.7-1.81		Anorthite	1.58
Aegirine	1.81		Chlorite	1.58
Corundum	1.76		Labradorite	1.57
Epidote	1.76		Talc	1.56
Staurolite	1.74		Andesine	1.56
Orthite	1.68-1.74		Quartz	1.55
Idocrase	1.72		Serpentine . . .	1.55
Kyanite	1.72		Cordierite . . .	1.54
Spinel	1.72		Kaolin	1.54
Chloritoid	1.71		Oligoclase	1.54
<i>High</i>			Nepheline	1.54
Zoisite	1.69		Albite	1.53
Enstatite	1.68		Gypsum	1.53
Augite, varies ..	1.68		Microcline	1.53
Olivine	1.68		Orthoclase	1.52
Fibrolite	1.67		Leucite	1.51
<i>Moderate</i>			<i>Very Low.</i>	
Hornblende	1.65		Hauyne	1.49
Andalusite . . .	1.64		Sodalite	1.48
Apatite	1.64		Natrolite	1.48
Anthophyllite ..	1.64		Opal	1.45
Tourmaline	1.63		Fluor	1.43

CHAPTER III.

Phenomena in Polarised Light.

It has already been remarked that in thin sections the component minerals of a rock to a large extent lose their colouration. In extreme cases a rock may even appear as an aggregate of colourless grains, divided by cracks and crystal faces, but presenting no marked characteristics by which they can be identified in ordinary light. Special means have therefore to be taken, without which little gain would result from the employment of the microscope in petrological research. Such a means has been found in the application of polarised light, and the information it affords is of the greatest service.*

DOUBLE REFRACTION. Every mineral refracts light to a certain extent, that is to say, makes the light deviate from a rectilinear path on passing into it. Indeed crystals belonging to any other than the regular system have more than one index of refraction. Such crystals are said to be birefringent, or to possess double refraction. In certain cases the birefringence of a mineral is so strong that two images of an object are seen when the latter is viewed through it. One of these is due to rays passing in a direction corresponding to that in which they would traverse a singly refracting medium like glass: the direction is called that of the *ordinary* ray. The other is due to rays which obey a different law of refraction: and the image is seen in the direction of the *extraordinary* ray. In some minerals the difference in the refractive indices of the two rays is slight, as in orthoclase. Such a mineral is said to be feebly birefringent, or to possess weak double refraction. Minerals like calcite, in which the two rays take widely divergent paths, are called strongly birefringent. In certain directions of particular minerals the refractive index of the two rays is the same, so that there is no double refraction. This is the case with basal

* For a full account of the optical properties of minerals, see Miers, *Mineralogy*, pp. 118-186. See also Evans, *Proc. Geol. Assoc.*, vol. xxi., 1909, pp. 79-94.

sections of tetragonal and hexagonal minerals: such minerals are said to be optically *uniaxial*. Minerals of the regular system have only one index of refraction for all directions through a crystal, and are said to be singly refracting or *isotropic*. Minerals belonging to the remaining three systems have two directions in which the birefringence is reduced to a minimum, and are said to be optically *biaxial*.

EXTINCTION. The phenomena dependent on the property of double refraction are observed by means of nicol prisms, one inserted under the stage of the microscope and known as the *polariser*, and the other inserted in the optic tube, known as the *analyser*. When the prisms are placed with their long diagonals at right angles, the latter has the effect of cutting off the polarised light transmitted by the former, and the field of the microscope is consequently dark. When the nicols are thus "crossed," a plate of glass or of any mineral crystallising in the regular system, will be found to bring about no change when placed upon the stage. Sections of doubly refracting crystals will be found, however, to interfere with the light passing through the polariser, and cause some at least of its components to pass through the analyser, except when placed in one of four definite positions during a rotation of the stage. These directions are at right angles to one another and are known as positions of extinction. Extinction may occur when the long axis of the crystal, as indicated by the outline or the cleavage traces, coincides with the diagonals of the nicols, as indicated by the cross wires in the eyepiece. In such a case the mineral is said to give *straight extinction*. In other cases the section is said to extinguish at an angle of so many degrees measuring from the nearest cross-wire. In practice the crystal is brought to the centre of the field, and its axis, as determined by the edges or the cleavages, is made to coincide with a cross-wire. A reading is then taken of the graduated circle at the edge of the stage, which is rotated until the maximum of darkness is reached. The angle is again read off, and the difference of the two readings (subtracted from 90, if over 45) gives the angle required. Longitudinal sections of the minerals crystallising in the tetragonal, hexagonal and rhombic systems invariably give straight extinction ;

in the oblique prismatic system the extinction is usually oblique, but may be straight ; while in the triclinic system it is always oblique. The extinction has a definite maximum for each mineral, thus in the common varieties of hornblende it does not attain 20° , while in augite it reaches 45° , so that these two minerals may be readily distinguished when several suitable sections are present in the rock slice. It is of course essential that a number of sections should be tried, except when a characteristically large angle is at once obtained, as a crystal may give any result *below* the maximum. A number of methods have been devised for determining the position of extinction with greater accuracy than can be done by the unaided eye, but as an error of a degree or so is of no importance in the case of slices made at random, they may be passed over without further remark.

INTERFERENCE TINTS. The *strength* of the double refraction of a mineral is a constant which it is important to determine. The colours to which doubly refracting minerals give rise when placed between crossed nicols are known as interference tints, and from the nature of these the double refraction can be gauged with considerable accuracy when a sufficient number of sections are to hand. The interference tints in a particular mineral will be found to vary greatly according to the thickness of the slice and the direction of the section through the crystal. The disturbing effects of thickness are, or should be, eliminated by the sections employed being as nearly as possible of the standard thickness of .03 mm., or $\frac{1}{3000}$ of an inch, while the highest tint observed among several crystals of the same mineral will, in all probability, be the characteristic maximum, or a close approximation to it. The succession of colours should be studied by means of a quartz wedge. On inserting the thinner end of the wedge between the crossed nicols, the lowest tint in the scale will be found to be a dull Payne's grey ; this graduates into a lighter grey, and then into white. The white shades into a rather dull yellow, and this again through orange into red. These colours constitute what is known as the first order. The second order commences with violet. This shades into blue, the blue into green, then come yellow, orange, and finally red. The student will

observe that violet, blue, and green are tints which do not occur in the first order while the remaining tints, though similar, are much less deep, but more vivid. The third order is practically a repetition of the second, the colours being paler, and with some of them rather slurred over, while the fourth order is practically reduced to delicate shades of mauve, green, and pink, the colours of still higher orders merging into a pearly white. The following table gives the maximum interference tints of all the most important rock-formers in slices of the standard thickness.*

First Order.

Payne's grey	...	Idocrase
"	....	Chlorite
Pale grey	...	Apatite
"	...	Melilite
"	...	Nepheline
"	...	Zoisite
White	...	Microcline
"	...	Orthoclase
"	...	Plagioclases (from Albite to Labradorite)
"	...	Corundum
"	...	Gypsum
"	...	Quartz
"	...	Cordierite
"	...	Staurolite
"	...	Topaz
Yellow	...	Andalusite
"	...	Anorthite
"	...	Enstatite
Orange	...	Wollastonite
"	...	Chloritoid
Red	...	Kyanite

Second Order.

Violet	...	Tourmaline
Blue	...	Fibrolite
Green	...	Anthophyllite
Yellow	...	Hornblende
"	...	Augite
Orange	...	Orthite (Allanite)†

* The student will find an exceedingly useful coloured plate, illustrating the tints in Levy and Lacroix's "Mineraux des Roches."

† Variable—often very weak, sometimes, indeed, the mineral is perfectly isotropic.

Third Order.

Violet	...	Scapolite (<i>variable</i>)*
"	...	Olivine
Blue	...	Epidote
Yellow	...	Biotite
"	...	Muscovite
Pink	...	Talc

Fourth Order.

Green	...	Zircon
White	...	Cassiterite (<i>variable</i>)
"	...	Sphene
"	...	Calcite and Dolomite
"	...	Rutile

In the above table there is no mention of the minerals which crystallise in the regular system. Some members, however, of this important group do exhibit an *anomalous*



FIG. 6.—ANOMALOUS DOUBLE REFRACTION OF GARNET round cavity in Granulite, Rusapi, Mashonaland. Photographed with crossed nicols. $\times 15$ diam.

double refraction. This is frequently the case with the larger crystals of leucite, garnet, etc., and in perovskite it is practically always to be observed. Anomalous double refraction has been accounted for by Mallard and others on the supposition that the minerals in which it is observed have, by repeated twinning, assumed the appear-

* This is for the varieties richest in lime : those with more soda show lower tints.

ance of a higher degree of symmetry than they really possess. To this it may be objected that the anomaly is entirely absent in many specimens of such minerals, and that the birefringence shown is invariably extremely low ; moreover, if such an explanation be accepted, we might just as well abolish the regular system altogether. It seems quite as reasonable to suppose that the phenomena are due to strain. Under pressure or torsion ordinary glass may be made to exhibit double refraction, and it is also shown by natural glasses (*e.g.* Krakatoa pumice), so there appears to be no reason why the same explanation should not be applied to the case of crystals.



FIG. 7.—LAMELLAR TWINNING OF TWO TYPES, in Plagioclase from coarse Granite, Lomagundi, Mashonaland. Crossed nicols. $\times 15$ diam.

EFFECTS OF TWINNING. Polarised light, when applied to rock slices, often reveals the structure known as twinning, even in minerals which give no indication of it in their external form. This is simply due to the fact that the interference tints vary according to the direction of section, and that in nearly all cases the individuals of a twin therefore differ in tint. For determinative purposes this fact may be made use of in various ways. It may serve as an aid to ascertaining the system of crystallisation ; or, in other cases, from its relation to the external form, may be of great assistance in identifying the particular mineral. In some cases repeated or *lamellar twinning* is found to be present, occasionally of more than one type,

and its mere existence, taken in conjunction with the features shown in ordinary light, is frequently sufficient to determine the mineral. Thus, microcline always shows a characteristic "cross-hatching" in polarised light, and the plagioclase feldspars are almost invariably made up of numerous lamellar individuals. In the latter case, the extinction angles of the different components can be made use of to determine the precise variety, as will be seen under the head of the feldspars.

INTERFERENCE FIGURES. Instead of examining a crystal in parallel light, that is to say, in the ordinary way with the rays of light all traversing it in practically the same direction, it may be viewed in convergent light by means of a condensing lens, which brings a cone of rays to a focus within the crystal. By such means the crystal is traversed by rays in all possible directions, and the same effect is produced as if a section could be cut in every direction at once. In those positions, therefore, which correspond to directions of extinction, the crystal remains dark; in other positions various interference colours are observed, according to the inclination of the rays, and the whole appearance is known as an interference figure.

To observe these figures a condenser and a high-power objective, such as a $\frac{1}{4}$ or $\frac{1}{6}$ inch, must be used, and further, since the image is formed near the objective, it must be brought into view either by (1) removing the eye-piece, (2) by holding an ordinary platyscopic or other pocket lens above the eye-piece, or (3) by inserting a lens of suitable focal length, known as a Bertrand lens, in the tube of the microscope. The figures may be well studied on a quartz plate, such as is usually supplied with petrological microscopes, and on a cleavage flake of mica (muscovite) as thick as a visiting card. In sections of this thickness brilliant systems of coloured rings will be seen to surround the optic axis or axes of the mineral. In the case of a *uniaxial* mineral like quartz, a dark cross will be observed, with its centre marking the *optic axis*. The colours of the rings surrounding it succeed each other in orders as described for parallel light, higher colours making their appearance as the distance from the centre increases. The character of the cross and rings does not change in any way on rotation of the stage of the microscope. The mica

gives a typical *biaxial* figure, showing two dark hyperbolæ (brushes), which unite four times during a rotation (at the extinction positions), to form a cross, of which one arm is broader than the other. The thin arm joins the optic axes, which are each surrounded by separate rings, with other 8-shaped and oval bands (lemniscates) enclosing them both. The intersection of the two arms indicates the point of emergence of a line known as the *bisectrix*: in the case of the mica, the acute bisectrix, as it bisects the acute angle between the optic axes. An obtuse bisectrix bisects the obtuse angle between the axes, and in a section cut perpendicular to it the axes are generally invisible, though some coloured rings may be seen.

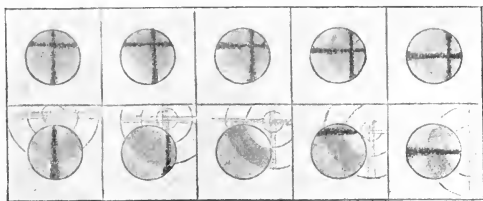


FIG. 8.—UNIAXIAL INTERFERENCE FIGURES. (After Levy & Lacroix.)

In rock sections, crystals are seldom to be found cut in the most favourable direction, *i.e.*, perpendicular to an optic axis, or to the acute bisectrix, as the case may be, and the thinness of the slice detracts much from the brilliancy of the figures. The crystal should be selected for examination which shows the lowest interference tints of any that are to be found in the slice, and, after centring with a low power, the double nose-piece is turned so as to bring the high power into action. The crystal must fill the whole field of the microscope when under the high power, unless no other doubly réfracting minerals are present. In the case of uniaxial minerals the complete cross will not be seen unless the section is parallel to the base, and therefore isotropic, or nearly so. One of the arms of the cross will, however, probably traverse the field as a dark bar. On rotation, this will move across the field, keeping all the time nearly straight, and approximately parallel to one of

the wires of the eye-piece, to be succeeded by another at right angles to it, which moves in a similar manner. Biaxial minerals, on the other hand, in sections perpendicular to an optic axis, shew a single curved bar, straightening out only when passing the centre of the field.

In biaxial crystals the apparent angle between the optic axes may vary greatly, from almost nothing, in fact, to nearly to two right angles. When the *optic axial angle*, and therefore the distance between the points of emergence of the two axes is very small, as in biotite, the interference figure will be a dark cross, which scarcely alters on rotation. It is, therefore, difficult to distinguish from that of an uniaxial mineral, and further ambiguity is introduced by the fact that some uniaxial minerals exhibit optical anomalies which result in a slight separation on rotation. As far as rocks are concerned, however, this is of little

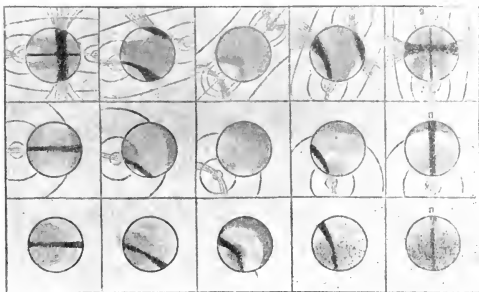


FIG. 9 —BIAXIAL INTERFERENCE FIGURES. (After Levy & Lacroix.)

practical importance, as the mere fact that a mineral is either uniaxial, or has a very small optic axial angle, is quite enough to restrict the possibilities very considerably among such a limited number of species as occur in rocks. In most cases the distinction is well marked, and convergent light is of great assistance in distinguishing between minerals whose optical properties are otherwise much alike. Thus, quartz is readily distinguishable from cordierite, and nepheline from the feldspars. A rough measure-

ment of the apparent axial angle will help much to confirm the determination of a doubtful mineral. This is most conveniently done by means of an eye-piece micrometer, or a series of circles on a glass, which can be slipped into the eye-piece. The distances between the points of emergence of the optic axes of minerals whose axial angle is known are noted on the scale, and from them the angle of any unknown mineral can be readily estimated.

DISPERSION. There is another point to be considered in connection with the optic axes of biaxial crystals, namely, that their position is not the same for light of all colours ; in fact, the interference figure seen in white light really results from a blending of all the effects that would be produced by each of the colours of the spectrum independently. Monochromatic light only gives rise to a succession of light and dark bands, but in white light, owing to the difference of position for each colour, the effect is to fill up all the gaps. The trace of the axis for red light is indicated symbolically by ρ , that for blue light by ν . The axial angle may be greater for red light than for blue, in which case the dispersion is said to be $\rho > \nu$. When it is less than for blue, it is expressed by $\rho < \nu$. With $\rho > \nu$, the dark hyperbolæ of the interference figure will be fringed with red on their convex side, in the case of $\rho < \nu$, with blue, the inner edges showing the reverse effect.

SIGN. Some minerals have their interference tints heightened when covered with a quartz wedge having its principal axis in the same direction as their own, while others have them lowered. In the former case the character of the double refraction is said to be *positive*, in the latter it is *negative*. In the case of minerals with weak birefringence (not exceeding that of quartz), a cleavage plate of gypsum of such thickness that it shows the first order red in polarised light, affords a good means of applying the test. The crystal is moved 45° from the extinction position, and the gypsum is placed upon it in such a way that its orientation and that of the crystal coincide. If the mineral is positive, it will lower the interference tint of the gypsum ; if negative, it will raise it. A quartz wedge may be used in a similar way. If, on inserting it above the slice, with its principal axis in the same direction,

its effect is added to that of the crystal, the latter is positive like the quartz. If, on the contrary, the tint is lowered as the wedge is moved until compensation and consequently darkness ensues, the crystal is negative. Compensation may thus be made to serve for ascertaining the order of the interference colour exhibited, as the latter must equal that of the quartz which produces the compensating effect.

The interference figure may also be utilised to determine the sign of the birefringence. In the case of the uniaxial minerals a $\frac{1}{4}$ wave-length plate of mica is used for the purpose. It is inserted in the slot usually provided in the optic tube of the microscope with its optic axial plane at 45° to the principal sections of the nicols, as indicated by

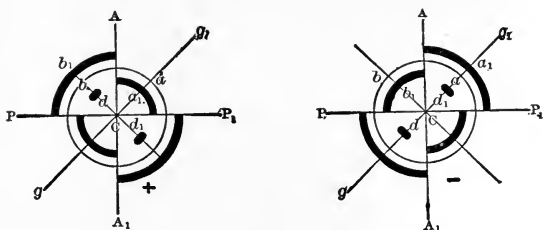


FIG. 10.—Determination of Sign. (After Rosenbusch).

the cross wires. In two diagonally opposite quadrants the rings of the interference figure will be shifted towards the centre, and in the other two away from it. In the case of a positive crystal, the rings contract where crossed by the axial plane of the mica, and expand in a direction at right angles to it. For a negative crystal the reverse holds good. It will be noticed that the optic axis opens out into two dark spots. If the line joining them would cross the axial plane of the mica, the mineral is positive; if the reverse, negative.

TRANSPARENT MINERALS CLASSIFIED ACCORDING TO
OPTICAL PROPERTIES.

ISOTROPIC.

Garnet,* Fluor,* Hauyne, Sodalite, Leucite,† Perovskite,† Diamond,* Analcime,* Spinel, Opal.*

DOUBLY REFRACTING : UNIAXIAL.

Positive : Chlorite (Pennine), Quartz, Zircon, Cassiterite, Rutile.

Negative : Apatite, Nepheline, Melilite, Beryl, Corundum, Tourmaline, Scapolite, Calcite, and Dolomite.

BIAXIAL : $\rho > v$.

Positive : Topaz, Gypsum, Augite, Sphene, Staurolite, Chloritoid, Labradorite.

Negative : Muscovite, Epidote, Wollastonite, Kyanite, Talc, Orthoclase, Microcline, Anorthite, Serpentine.

 $\rho < v$.

Positive : Albite, Enstatite, Barytes, Olivine, Fibrolite, Zoisite, Anthophyllite, Chlorite.

Negative : Hypersthene, Hornblende, Biotite, Cordierite.

* Sometimes show anomalous double refraction.

† Generally show marked anomalous double refraction.

CHAPTER IV.

The Rock-Forming Minerals: (I) Elements and Oxides.

ELEMENTS.

Carbon occurs in rocks as Graphite and as Diamond, as well as in an indefinite coaly condition. Graphite ($H=1$; $G=2$) is opaque and structureless, occurring as black granules or films in slates, marble, etc., and forming quite an important constituent of a few schists. The diamond (Regular; $H=10$; $G=3.52$), though of such restricted occurrence, is entirely found as a rock-former, but its hardness renders the preparation of sections containing it practically impossible. Owing, however, to its resistance to acids, including HF, it is readily isolated, and the crystals, usually octahedra or dodecahedra, show characteristic triangular markings on the faces. R.I. very high (2.417). Anomalous double refraction is usually shown, isolated crystals or cleavage flakes half a millimetre in thickness giving yellow of the first order, but no definite interference figure is seen in convergent light. Strongly heated with nitre it burns entirely away.

The diamond is almost invariably found in a volcanic rock of ultrabasic composition known as "blue-ground" or sometimes as "Kimberlite." This peculiar rock, which may be regarded as a garnet and ilmenite-bearing serpentine, occurs filling volcanic vents or "pipes" at numerous localities round Kimberley in Cape Colony, at Jagersfontein and other places in the Orange River Colony, at several localities near Pretoria in the Transvaal, in the Bembezi district of Rhodesia, and near Bingara, New South Wales. Diamonds have also been detected in the so-called "eclogite" inclusions of the Newlands Mine, near Kimberley, and the Roberts-Victor Mine in the Orange



FIG. 11.—A TYPICAL DIAMOND.

River Colony, as well as in dolerite (?) near Inverell, New South Wales. In Brazil, India, Borneo, British Guiana, German S.W. Africa, and near all the above-mentioned places, diamonds have been worked in sandstones, conglomerates, gravels, and other fragmental rocks. They have also been detected in several meteorites, and the general composition of their usual matrix is closely allied to that of the ordinary meteoric stones.

Iron: regular; $H=4-5$; $G=7.3-7.8$; turns into hydrated oxide (limonite) on weathering. Like the diamond it is found native only as a rock-former. It may be detected by its magnetic properties, added to its solubility with effervescence in cold dilute hydrochloric acid. A delicate test is the treatment of a thin slice or the powdered rock with copper sulphate solution, when the presence of iron is manifested under the microscope by the production of a pink coating of metallic copper.

Analyses of Native Iron.

			I.—Ovifak, Greenland. (Lindstrom.)	II.—Toluca Meteorite. (Meunier.)	III.—Rowto Meteorite. (Flight.)
Iron	..	..	93.24	92.0	91.250
Nickel	..	..	1.24	7.5	8.582
Cobalt	..	..	.56	not det.	.371
Copper	..	..	.19	—	trace
Phosphorus	..	..	.03	—	—
Sulphur	..	..	1.21	—	—
Chlorine	..	..	.16	—	—
Carbon	..	..	2.30	—	—
Hydrogen	..	..	.07	—	—
Silica	..	..	.59	—	—
Potash	..	..	.08	—	—
Soda	..	..	.12	—	—
			99.79	99.5	100.203

Iron has been detected in basalt at Ovifak in Greenland, in minute grains in the Antrim flows, and in the olivine rock of New Zealand; it also occurs abundantly in most meteorites, always in the form of an alloy with nickel, which shows characteristic etched figures when a polished surface is treated with dilute acids, or preferably with bromine water.

OXIDES.

Quartz: SiO_2 ; Hexagonal; $H=7$; $G=2.65$. Is not attacked by acids except HF, and resists all natural chemical agencies, so that it never shows signs of de-

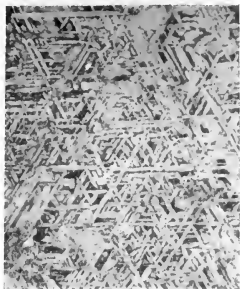


FIG. 12.—NICKEL-IRON OF THE TOLUCA METEORITE.
Etched to show Widmannstätten's figures.

composition. Fused with potash or soda it forms a soluble silicate.

Always transparent and colourless in slices. Occasionally zoned by inclusions; sometimes occurs in skeleton

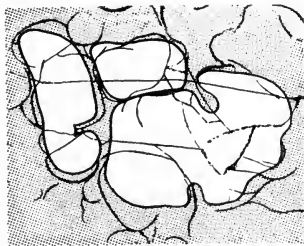


FIG. 13.—CORRODED QUARTZ PHENOCRYSTS. In Rhyolite, 2,160-foot level, Kimberley Mine, Kimberley, Cape Colony. $\times 30$ diam. Showing quartz and groundmass alike traversed by a rude system of Perlitic cracks.

crystals. Is usually allotriomorphic, being the last product of crystallization from a fused magma; when

idiomorphic, as in certain rhyolites and granophyres, it occurs in pyramids, occasionally combined with the prism, though prism faces are always subordinate. Never twinned. Shows no signs of cleavage, but is traversed by irregular cracks. Crystals often contain glass, liquid, and gas inclusions, sometimes in the form of negative crystals, also needles of apatite, rutile, zircon, fibrolite, etc.

Refractive index low, 1.55; double refraction weak and positive. Its surface, therefore, appears smooth, while the interference tints do not exceed white or dull yellow of the first order except in thick slices. Gives straight extinction. Spectral polarisation is sometimes shown, that is to say that different parts of a crystal extinguish in succession as the stage of the microscope is rotated, a state of affairs due to strain. The uniaxial interference figure in convergent polarised light is often of use in distinguishing quartz, in doubtful cases, from certain other minerals which resemble it.

Silica, free and in combination, must form at least two-thirds of the earth's crust. Free silica, in the form of quartz, is very abundant in rocks of every description, being present in all the more acid igneous and metamorphic types, and in the clastic stratified series, of which it frequently forms nearly the whole bulk.

Chalcedony: SiO_2 ; cryptocrystalline; $H=7$; $G=2.62$; is attacked by a boiling solution of soda or potash; occurs in fibrous or confused aggregates, often spherulitic.

R.I. weak (1.53). Double refraction about the same as for quartz, but negative.

Chalcedony never occurs as an original constituent of igneous rocks, but is frequently formed in cavities and vesicles. It makes up the mass of cherts and flints and is also present in many slates, etc.

Corundum: Al_2O_3 ; Hexagonal; $H=9$; $G=4$. Unattacked by acids or alkalis.

Colourless, as a rule, but sometimes blue and occasionally red or brown. Crystallizes in pyramidal or tabular forms, giving an elongated vertical and an hexagonal transverse section, but irregular granules are frequent. Sometimes zoned. Shows a plane of parting parallel to the faces of the fundamental rhombohedron of its crystalline form.

Analyses of Rock-forming Corundum.

(M. F. CONNOR.)

I.—Blue variety in "Syenite" of Dun- gannon, Ontario, Canada.				II.—Brown variety in Corundum — micro- perthite rock of Craig- mont, Ontario.			
Al ₂ O ₃	..	..	96.90				95.58
Fe ₂ O ₃	..	..	.76				2.10
CaO	..	..	.46				.48
MgO	..	..	1.00				1.00
H ₂ O	..	..	.88				.84
<hr/>				<hr/>			
100.00				100.00			

R.I. very high, 1.76; double refraction weak; interference tints not exceeding red of the first order. Shows pleochroism when strongly coloured. For sapphire O is blue and E is greenish to colourless.

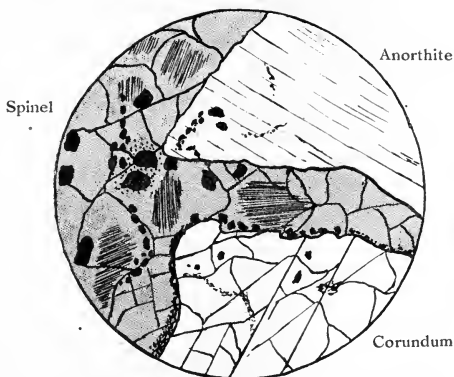


FIG. 14.—CORUNDUM-BEARING ROCK. Tuli district, Rhodesia. $\times 25$ diam. (From *Geol. Mag.*)

The variety emery forms granular masses in highly metamorphosed and presumably contact altered rocks. Other varieties are found in granulite, gneiss, syenite, picrite, and serpentine, as well as in crystalline limestones.

Hæmatite: Fe₂O₃; Hexagonal; H=6; G=5. Soluble in hydrochloric acid.

Opaque or red. By reflected light shows a dull metallic lustre and a purplish-black colour; earthy varieties are dull red.

As an original constituent of igneous and metamorphic rocks occurs in rhombohedral or tabular crystals with plane of parting parallel to the rhombohedral faces, also in thin scales or irregular granules. It is frequently disposed along definite directions in crystals of other minerals. The earthy red variety is always secondary, being derived from the oxidation of magnetite or from the decomposition of other ferri-ferous minerals.

R.I. very high (1.90).

Hæmatite is sparingly but widely distributed in the igneous rocks, often as an inclusion in other minerals, to which it imparts a reddish tinge. It is more abundant in the sedimentary and metamorphic rocks, being a frequent cementing material of sandstones. Sometimes forms the bulk of sedimentary deposits of limited extent, which are occasionally transformed by pressure, etc., into hæmatite schist.

Spinel.— $\text{Al}_2\text{O}_3\text{MgO}$. Regular. $H = 7\frac{1}{2}$; $G = 4$. Un-attacked by acids and unaffected by weathering. It includes several varieties, those corresponding most closely with the above formula being transparent and colourless to pink, while those in which iron replaces the alumina (*Pleonaste*), or zinc the magnesia (*Gahnite*) are green when transparent. The chrome spinel, *Picotite*, is yellow to brown, sometimes almost opaque.

The spinels crystallize in well-defined octahedra, giving square sections in many directions; often granular; no cleavage traces. Twins on faces of octahedron; such twins are often called "spinel-twins."

R.I. very high (1.71). Dark between crossed nicols.

Occur sparingly in granulites and gneisses, also in the basic igneous rocks, especially the variety *picotite*.

Chromite.— $\text{Cr}_2\text{O}_3\text{FeO}$. Regular. $H = 5\frac{1}{2}$; $G = 5$. Little affected by acids. Before the blowpipe gives green beads with borax, and opaque yellow with carbonate of soda. The last reaction is very delicate and highly characteristic, but it is liable to be masked by manganese should that metal be present.

Black and opaque, with submetallic lustre, to translucent

grey in very thin sections; usually in rounded grains, sometimes with an approach to crystal outline.

R.I. extremely high (2.096). Dark between crossed nicols.

Occurs in a few of the more basic igneous rocks, such as the picrites and serpentines.

Magnetite.— Fe_2O_3 . Regular. $H = 7$; $G = 5$. Soluble in HCl. Strongly magnetic, being readily separable from other constituents of a rock by applying a magnet to the powder. Weathers to hæmatite or limonite.



FIG. 15.—SKELETON CRYSTAL OF MAGNETITE. In dolerite, near Bulawayo

Opaque in the thinnest sections; greyish metallic lustre by reflected light.

It occurs in octahedra, or as granules, sometimes very irregular in shape. Occasionally forms skeleton crystals. Sometimes twinned on O: no cleavage traces. R.I. very high.

Occurs in nearly all the igneous rocks, and is widely distributed in the metamorphic ones; also found in sands, sandstones, etc.

Rutile.— TiO_2 . Tetragonal. $H = 6\frac{1}{2}$; $G = 4.2$. Insoluble in HCl or HF, but soluble in hot H_2SO_4 ; fused with carbonate of soda and then boiled with tin foil in HCl it gives a violet colouration. Sometimes alters to the whitish substance called leucoxene, but resists ordinary surface weathering almost completely.

Analyses of Spinellids.

	I. Rose Spinel Ceylon. (Abich.)	II. Pleonaste Peekskill, N.Y. (Wolle.)	III. Magnetite Magnet Cove. (Harrington.)	IV. Magnetite Lofoten, Norway. (Vogt.)	V. Picotite Cuillins, Skye. (Pollard.)	VI. Chromite Dun Mtn. N.Z. (Miers.)
SiO_2	2.02	—	—	—	1.19	—
TiO_2	—	—	2.40	5.29	.34	—
Al_2O_3	69.01	60.79	10.37	—	46.54	12.13
Cr_2O_3	1.10	—	—	—	17.55	56.54
Fe_2O_3	—	5.26	59.01	62.03	6.01	—
FeO	.71	21.74	16.82	32.68	10.10	18.01
MnO	—	—	2.10	—	[CaO.43]	—
MgO	26.21	12.84	9.47	—	18.35	14.08
(CoNi)O	—	—	—	—	.24	—
H_2O	—	—	—	—	—	—
	99.05	100.63	100.17	100.00	100.75	100.76

Deep brown, reddish or yellowish to colourless; in large granules or small prisms, also in skeleton crystals (sagenite); perfect prismatic cleavage; twinning on the plane 010 is common, giving rise to the knee-shaped forms, also parallel to 301; lamellar twinning on the former law is sometimes shown; the coloured varieties show pleochroism.

The refractive index, 2.76, and double refraction, are higher than for any other rock-former; the interference tints are, therefore, usually greys of a high order, and the smaller microlites appear quite opaque. Positive.

Rutile occurs chiefly as inclusions in other minerals in many igneous rocks; also in slates, phyllites, and the more highly metamorphic rocks, especially near contacts. It is frequently found in the heavy residues obtained by washing sands, as in the Bagshot beds near London. (See figure, Chap. xiv.).

Cassiterite.— SnO_2 . Tetragonal $H = 7$; $G = 6.9$. Before the blowpipe with carbonate of soda, or potassium cyanide on charcoal, it may be reduced to metallic tin. There is, however, a simpler means of testing. The mineral powder supposed to contain it is laid upon a piece of zinc sheet or foil, in any convenient receptacle, and a few drops of hydrochloric acid are poured on it. After a minute's effervescence a greyish metallic coating of tin will cover the grains of cassiterite. The presence of tin can be verified by removing the zinc, dissolving the deposited metal in fresh hydrochloric acid and adding a drop of gold chloride solution, when the well-known purple colour may be observed ("purple of Cassius"). Cassiterite is not attacked by acids, and is impervious to the ordinary processes of weathering.

Colourless, yellow, and red, to deep brown or even opaque; occurs in stout prisms, also granular. Frequently zoned. Geniculate twins common; longitudinal sections give straight extinction, and transverse ones diagonal extinction; no definite cleavage.

R.I. very high, 2.03; D.R. usually strong and positive, but somewhat variable.

Occurs in certain granites and their offshoots, also in the adjacent contact rocks, and in sands, etc., derived from them.

Ilmenite.— FeOTiO_2 . Hexagonal. $H = 5\frac{1}{2}$; $G = 4.5$. Attacked by hot HCl and H_2SO_4 , if frequently partly altered into leucoxene. The alteration of ilmenite sometimes commences on the margin and proceeds inwards until all traces of the original mineral have disappeared. In other cases it proceeds along two sets of parallel planes intersecting at angles of 60 and 120 degrees. Ilmenite is frequently intergrown with magnetite; the latter may be removed by hot HCl , and a skeleton of ilmenite left behind.

Analyses of Rock-Forming Ilmenite.

Common Variety.			Magnesian Variety.	
Upway, Victoria.			Balangoda, Ceylon.	
(Richards.)			(Crook & Jones.)	
TiO_2	..	..	67.28	56.08
FeO}	..	..	31.92	24.40
MnO}	..	..	trace	Fe_2O_3 5.43
MgO}	..	..	.80	14.18
			100.00	100.09
$G = 4.86$			$G = 4.25$	

Opaque. Shows sub-metallic lustre by reflected light; considerably duller than magnetite. Crystallizes, like



FIG. 16.—SKELETON CRYSTAL OF ILMENITE.
Porphyrite, Wood's Point, Victoria, Australia.
Australia. $\times 60$ diam.

hæmatite, in rhombohedral or tabular forms; skeleton crystals are common. Frequently granular, often in very irregular branching forms. Plane of parting parallel to the rhombohedral faces, becoming more strongly marked

through decomposition, as the leucoxene to which it gives rise extends most readily along this plane. R.I. extremely high.

Common in the more basic igneous rocks, and also occurs in certain schists, etc. Abundant in the "black sand" of many alluvial deposits.

CHAPTER V.

The Aluminous Silicates.

THE most important of the rock-formers belong to the class of silicates which are rich in alumina. Where the alumina is accompanied by the alkalis, or lime, or both, we have minerals belonging to the feldspar or feldspathoid groups. The other highly aluminous silicates comprise some important contact minerals, far more restricted in their occurrence, however, than the feldspars, while we may also include as somewhat aberrant members of the group scapolite, which is a lime alumina silicate and chloride, and those micas into the constitution of which iron and magnesia scarcely enter. This grouping is one to which exception

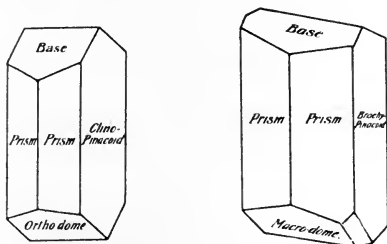


FIG. 17.—FELSPAR CRYSTALS. (Orthoclase and Plagioclase.)

may possibly be taken, but the changes that are so frequently seen from andalusite and orthoclase into muscovite and other alteration products, and of the lime-feldspars into scapolite, etc., evidence the close relationships of the minerals. Muscovite is also sharply differentiated from its mineralogical ally, biotite, with which it is usually classed, by its mode of occurrence in most rocks, apart from the particular type of granite in which the two minerals occur together.

The Feldspars are, of course, by far the most important

members of the present group, constituting as they do the great bulk of many rock masses. They belong to two different systems of crystallization, their forms, however, being almost identical, and they vary much in chemical composition, though in directions strictly correlated with definite variations in their physical properties. Orthoclase, the potash felspar, stands by itself as a member of the oblique prismatic system of crystallization. Microcline, which is closely allied to it but contains variable amounts of soda, is anorthic. The difference of its angles, however, from those of orthoclase is scarcely measurable ; though, on the other hand, its microscopic structure, as shown in polarised light, renders its distinction a matter of the greatest ease. Besides these, we have the group of plagioclases, readily discriminated for the most part from orthoclase, and microcline, but not so easily separated from one another, though such a separation is of great importance for classificatory purposes. Nevertheless, methods have been devised which enable a distinction to be made without great difficulty, in most instances, and some account of these is given below.

Orthoclase. — $K_2OAl_2O_36SiO_2$. Monoclinic. $H = 6$. $G = 2.56$. Is not appreciably attacked by HCl . When fused with carbonate of soda before the blow-pipe, the violet potassium flame colouration may be seen through blue glass. Heated with cobalt nitrate, turns a bright blue.

When fresh, as in Adularia and Sanidine, is transparent and colourless. Has a strong tendency to alter into kaolin and scaly muscovite, with separation of quartz ; it then becomes cloudy or dirty-looking, and sometimes almost opaque. Varieties coloured pink or flesh-colour by iron are common, the colour showing well by reflected light. Decomposition often results in yellowish or brownish stains.

In many rocks orthoclase occurs in good crystals in which the prism, basal plane, orthodome, and clinopinacoid predominate ; the last-named face being especially well developed. Twinning takes place commonly in three ways. The most usual type is known as the Carlsbad twin ; it is an interpenetration twin, with a divisional line showing general parallelism to the clinopinacoid.

This line is frequently very irregular. In the Baveno type the twin plane is parallel to the clinodome. In the Manebach type the base is the twinning plane.

Orthoclase occurs in crystallographic intergrowth with albite and other anorthic feldspars to form perthite, or micropertthite, the structure being readily recognised under the microscope. It also occurs intergrown with quartz, and forming zones round the more basic feldspars.

R.I. low (1.52). D.R. very weak, the interference tints not exceeding blue-grey of the first order. In some metamorphic rocks it forms clear granules, showing no sign of cleavage traces, and can only be distinguished from quartz by its biaxial interference figure in convergent light, and from albite by its chemical behaviour. It has two perfect cleavages parallel respectively to the basal plane and the clinopinacoid, and occasionally shows an imperfect one parallel to the orthopinacoid. The extinction is parallel to the cleavage traces when these latter intersect at right angles. The two individuals of a Carlsbad twin may extinguish straight, and therefore simultaneously, but they never otherwise give symmetrical extinctions.

Orthoclase is very common in the acid and intermediate igneous rocks, also in schists and gneisses, and in some clastic rocks, usually in a somewhat decomposed condition.

Microcline is similar in composition and general properties to orthoclase, but is usually considered as crystallising in the triclinic (anorthic) system. It often contains a good deal of soda (anorthoclase).

The interference tints are rather lower than those of orthoclase, but its chief distinguishing feature is the presence of a grated structure, due to two intersecting systems of twin lamellæ. The lamellæ are never very sharply defined (see figure), but appear spindle-shaped, and shade into one another with perfect gradation, usually being thickest at their points of intersection.

It is rare among the igneous rocks, except in the plutonic members of the acid series, in which it is frequently far commoner than orthoclase over large areas of country. It is very abundant in the gneisses and other meta-

morphic rocks, and sometimes occurs as derived grains in sedimentary deposits.

Anorthoclase differs from the above only in containing a considerable proportion of soda. There do not seem to be any good grounds for separating it from microcline, as it shows similar cross twinning, and all microclines contain some soda. It can only be identified with certainty by chemical methods.

The *Plagioclases* form an isomorphous group graduating into one another by a progressive alteration in the proportions of soda and lime they contain. They may all be considered as combinations of the *Albite* molecule, Na_2O .



FIG. 18.—MICROCLINE, cut obliquely to the twinning, and showing inclusions of Plagioclase. + nicols, $\times 30$ diam.

$\text{Al}_2\text{O}_3.6\text{SiO}_2$ (pure soda felspar) with that of *Anorthite* $2(\text{CaO}.\text{Al}_2\text{O}_3.2\text{SiO}_2)$, (pure lime felspar). Some of the lime or soda is frequently replaced by potash, or even baryta and strontia, but few accurate observations have been made with regard to the extent to which this takes place.

Well-developed crystals are seldom found, but when they occur the forms are very similar to those of orthoclase, though their symmetry is not so high, as they belong to the anorthic system. The angle between the brachypinacoid and the basal plane is not 90° as in orthoclase, but varies from 93° to 94° .

The group is characterised, as a rule, by lamellar twinning on the brachy-pinacoid, but the absence of twin lamellation must not be taken as indicating with certainty that a felspar does not belong to the albite-anorthite series, though the recent discovery that orthoclase is the unstriated felspar in a number of quite basic rocks seems to show that it generally holds good. On the other hand, the presence of twin lamellation is a conclusive proof that the felspar which shows it belongs to this group.

Besides the albite lamellation parallel to the brachy-pinacoid, some of the group, especially the more basic varieties, show lamellar twinning parallel to the prism of the second order (pericline type). This cross-twinning is readily distinguishable from that exhibited by microcline on account of the sharp definition of the lamellæ. Ordinary twinning on the Carlsbad plan is common, while the Baveno and Manebach twins also occur. Skeleton crystals are not very often seen, but microlites are extremely common.

The specific gravity, refractive index, double refraction, and extinction angle all increase with the increasing predominance of the anorthite molecule.

The most basic types usually show the broadest twin lamellæ. The more acid microlites are usually thin prisms; the more basic ones assume a tabular form parallel to the brachy-pinacoid. Zoning is frequent, the outer portions being usually more acid than the interior. The lamellation is considered by some writers to be of secondary origin, but, on the other hand, the plagioclases of the metamorphic rocks frequently show no signs of either twinning or cleavage, and their water-clear granules can only be distinguished from quartz by their bi-axial figure or by chemical tests.

The principal cleavages are parallel to the base and brachy-pinacoid, intersecting at an angle of about 86° in all varieties.

TABLE OF SPECIFIC GRAVITIES, EXTINCTION ANGLES ON CLEAVAGE FLAKES AND REFRACTIVE INDICES OF AVERAGE FELSPAR.

	G.	Extinction Angles.	Mean R.I.
Orthoclase	2.57	0 on base; — 5° to 7° on Cl-pin	1.524
Microcline	2.57 + 15°30'	„ ; — 5° on Br-pin	
Anorthoclase	2.59	0 to +5° „ ; — 6° to 12° „ „	
Albite (Ab)	2.62 + 4°30'	„ ; — 19° „ „	1.535
Oligoclase (Ab ₃ .An)	2.66 — 1°4'	„ ; — 4°46' „ „	1.542
Andesine (Ab. An) ...	2.69 — 5°10'	„ ; — 16° „ „	1.558
Labradorite (Ab.An ₃)	2.72 — 17°40'	„ ; — 29°28' „ „	1.570
Bytownite (Ab. An ₆)	2.74 — 27°33'	„ ; — 33°29' „ „	1.576
Anorthite (An)	2.75 — 37°	„ ; — 36° „ „	1.582

Two zones are important in this connection, and are comparatively easy to recognise. These are the direction of elongation corresponding to the edge 001 : 010, and that perpendicular to the brachy-pinacoid (010). In the first case the cleavage traces and the twin lamellations are parallel to the long axis. In the second case the sections are nearly symmetrical, and the two cleavages cross each other nearly at right angles. The twin lamellæ extinguish symmetrically on either side of the twin plane. The extinctions, as given by Messrs. Levy and Lacroix, are as follows :—

VARIETY.	ZONE 001 : 010.	TO 010.
Albite .. ..	.. + 20°	— 18°
Oligoclase .. ..	.. + 5°	+ 4°
Basic oligoclase ..	.. 0°	+ 12°
Andesine .. ..	.. — 18°	+ 21°
Labradorite .. ..	.. — 31°	+ 32°
Anorthite . . .	.. over 45°	over 50°

In both cases ambiguity exists between albite and andesine, but this is of little real moment, as they occur in quite different classes of rocks, and there is seldom any chance of confusion. It is entirely removed by observing certain other characteristics. Thus a feldspar having a greater specific gravity than quartz must be at least as basic as oligoclase, while those with a higher refractive index must be andesine or an even more basic variety. Anorthite gelatinises with boiling hydrochloric acid; the other feldspars are but little attacked.

Albite and oligoclase are very generally distributed in the acid and intermediate igneous rocks, while the former

especially is very abundant in metamorphic rocks, where it is liable to be mistaken for quartz. Andesine is abundant in the intermediate igneous rocks, while labradorite is a very common constituent of the basic and sub-basic groups. Bytownite and anorthite are confined to the basic and ultra-basic series. All the plagioclases may occur as clastic grains in the sedimentary rocks.

The Felspathoids are a group which replace or co-exist with the feldspars in those rocks which contain unusually large percentages of the alkalis, or are deficient in magnesia. They are not, however, chemically analogous to the feldspars, but rather to such basic silicates as olivine, and they never occur in the acid series. Nepheline and leucite are the most important of the group, but even these are only found in certain restricted areas.

Analyses of Felspars.

	<i>Ortho- clase from granite of Wood- stock, Maryland, U.S.A. (Bascom.)</i>	<i>Ortho- clase from Pegmatite of Amelia, Va., U.S.A. (Watson.)</i>	<i>Ortho- clase from "Neph. Syenite" of Coul More, Scotland. (Pollard.)</i>	<i>Albite from Pegmatite of Amelia, Va., U.S.A. (Watson.)</i>	<i>Oligo- clase from Pegmatite of Ytterby, Sweden. (Berzelius.)</i>	<i>Labradorite from Flakstadö, Norway. (Vogt.)</i>
SiO ₂	65.96	65.37	63.84	67.06	61.55	52.42
Al ₂ O ₃	19.53	18.74	18.87	21.72	23.80	31.25
Fe ₂ O ₃	.24	.13	.68	MgO .03	.80	—
CaO	.18	.27	.18	.59	3.18	11.98
K ₂ O	12.92	12.98	14.76	.38	.38	.97
Na ₂ O	1.13	2.49	1.23	10.01	9.67	3.44
H ₂ O	—	—	.30	—	—	—
	99.96	99.98	99.86	100.79	99.38	100.06
Sp.Gr. =		2.501	2.55	2.618		2.708

Nepheline, 3Na₂O, K₂O, 4Al₂O₃, 9SiO₂, belongs to the hexagonal system. H = 6 : G = 2.6. Some of the soda is usually replaced by potash. The potassium flame colouration may be observed before the blow-pipe when the sodium flame is cut off by blue glass. Soluble in hydrochloric acid with separation of gelatinous silica. Readily alters to zeolites.

In the igneous rocks which have consolidated at or near

the surface, nepheline usually forms good crystals, hexagonal prisms terminated by basal planes, giving nearly square vertical and hexagonal transverse sections. The allotriomorphic variety, found in plutonic rocks, has been unnecessarily distinguished by the name *Elaeolite*. There

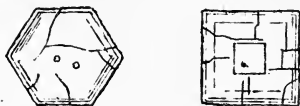


FIG. 19.—BASAL AND LONGITUDINAL SECTIONS OF NEPHELINE, in "Phonolite" of Brux, Bohemia.
× 50 diam.

are two cleavages, parallel respectively to the prism and the base, which are usually most obvious in the massive variety. Zoning is common, as shown in the figures.

Nepheline, when unaltered, is clear and colourless under the microscope, but the formation of zeolites, principally natrolite, is frequently observed along the cleavage cracks.

The refractive index is low (1.54). Double refraction and interference tints very weak, the latter not exceeding grey of the first order. Basal sections are isotropic, but show a dark cross in convergent polarised light.

Nepheline occurs in certain intermediate and basic rocks, principally belonging to the eruptive series. It is comparatively rare in the plutonic types, but is present in a few rocks allied to the diorites and dolerites in composition, but frequently termed nepheline or elaeolite syenites.



FIG. 20.—SECTIONS OF LEUCITE, in Basalt of Vesuvius.
× 50 diam.

Leucite, $K_2O \cdot Al_2O_3 \cdot 4SiO_2$. Regular. $H = 5\frac{1}{2}$; $G = 2.5$. Is not noticeably attacked by HCl , except when powdered; does not gelatinize. Gives potassium flame colouration before the blow-pipe. Readily alters into analcime and other decomposition products.

When fresh it is clear and colourless and crystallizes in trapezohedra, giving eight-sided, or, when imperfectly developed, rounded sections. The zoning by inclusions, which are disposed parallel to, or at right angles to, the faces, is very characteristic and often affords a ready means of identifying the mineral. Anomalous double refraction is frequently exhibited by the larger crystals; this disappears on heating to 440° . There is no noticeable cleavage. R.I. low (1.51).

Leucite is of comparatively rare occurrence, being only found in a few basic lavas and dykes of late geological age.

Hauyne and *Nosean* are similar, being both silicates of soda and alumina, with some lime and sulphuric acid.



FIG. 21.—NOSEAN, Rieden, Eifel, Germany.
× 50 diam.

The varieties with most soda are called nosean, and those with most lime hauyne. Regular. $H = 5\frac{1}{2}$; $G = 2.4$. Gelatinize with HCl, and become blue, if not already so, on heating in sulphur vapour. Give a sodium flame before the blow-pipe; readily alter to aggregates of natrolite and calcite, etc. Usually colourless or blue (*e.g.*, Lapis Lazuli), in slices. In the case of hauyne, even colourless varieties usually show local patches of blue; sections are generally rectangular or hexagonal; rarely found except in definite crystals. Zoning is common, parts of the crystal being frequently dusty-looking and almost opaque, owing to inclusions.

These two minerals are occasionally found in intermediate and basic rocks, also in metamorphosed limestones, sometimes forming patches of lapis lazuli.

Sodalite is a soda silicate related to nosean and hauyne, but containing chlorine in place of sulphuric acid. Regular. $H = 5\frac{1}{2}$ to 6; $G = 2.3$. Readily soluble in HCl, yielding cubic crystals of salt on evaporation. Noticeably attacked

even by acetic acid ; readily alters to natrolite, etc. When unaltered is clear and colourless, often with violet or blue patches. The most usual crystals are octahedra or dodecahedra, but it often occurs allotriomorphic. Cubic cleavage is sometimes shown. R.I. very low (1.48), so much so that it appears somewhat pitted. Dark between crossed nicols. It occurs sparingly in certain intermediate, basic, and ultra-basic rocks rich in alkali.

Melilite, $12\text{CaO} \cdot 2\text{Al}_2\text{O}_3 \cdot 9\text{SiO}_2$. Tetragonal. $H = 5$; $G = 3$. It is completely decomposed by HCl , giving needles of gypsum on addition of H_2SO_4 . It readily undergoes alteration.

In thin sections it is colourless, or slightly yellow. By reflected light it looks dull white or yellowish. It crystallizes in tabular forms bounded by the basal plane and

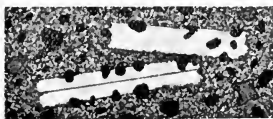


FIG. 22.—MELILITE, in Groundmass of Spiegel River Picrite. $\times 100$ diam.

prism of first order, frequently combined with the second order prism (100) or the pyramid (310). The outline is then rectangular or octagonal in basal sections. It often occurs in irregular plates, or gives lath-shaped sections like feldspar. These are elongated in the direction of the basal plane, and give straight extinction. Cleavage is shown parallel to the base, but peculiar striations ("peg structure") are sometimes observed parallel to the prism. Refractive index = 1.63. Double refraction very weak and negative. The yellowish variety may exhibit slight pleochroism in shades of yellow.

Melilite frequently occurs in those rocks which contain nepheline and leucite, and occasionally also in ultrabasic rocks, from which the latter are absent. It was probably an original constituent of the diamantiferous "blue-ground" of Kimberley and elsewhere.

Scapolite is a silicate of alumina, lime, and soda,

with chlorine. Tetragonal. $H = 5\frac{1}{2}$. $G = 2.6$. Readily alters to zeolitic aggregates. When fresh, is colourless and transparent, but is often dull and clouded, especially along cleavage cracks. Seldom shows crystal outline; cleavage perfect, parallel to the prism (110), a less perfect parting parallel to the prism (100) is also noticed at times. R.I. low (1.55). D.R. usually strong (negative), the interference tints reaching well into the second order. It varies considerably, however, according to composition, from moderate in the soda-bearing to very strong, in the most lime-bearing varieties. Gives straight extinction (parallel to the cleavage traces). Occurs in crystalline



FIG. 23.—SCAPOLITE. Basal Section, showing First and Second Order Prism Faces and inclusion of Calcite. In Crystalline Limestone, near Kanshi, N.W. Rhodesia. $\times 50$ diam.

limestones, amphibolites, and other contact altered rocks, especially in the neighbourhood of great granite masses.

The next group of aluminous silicates comprises those which are almost pure silicates of aluminium. They rarely, if ever, occur as primary constituents of the igneous rocks, but are usually produced under circumstances of great pressure, even when largely the result of thermal metamorphism.

Andalusite, $Al_2O_3 \cdot SiO_2$. Orthorhombic. $H = 7\frac{1}{2}$. $G = 3.2$. Is not attacked by acids. Like all the members of this group, it gives a blue colouration with cobalt nitrate before the blow-pipe. Alters to muscovite and weathers

to kaolin. Transparent and colourless in sections, unless decomposed, when it is cloudy and even opaque. Usually occurs in more or less well-defined columnar crystals, which are generally simple prisms (angle $90^{\circ} 50'$), terminated by basal planes. Basal sections are nearly rectangular; longitudinal sections are rectangular, and show the cleavages parallel to the prism, though this is sometimes unrecognisable in slices. Never twinned; sometimes granular.

R.I. fairly high (1.64); double refraction moderate; negative, giving interference tints up to yellow and orange of the first order. Gives straight extinction in longitudinal sections, those parallel to the base extinguishing diagon-

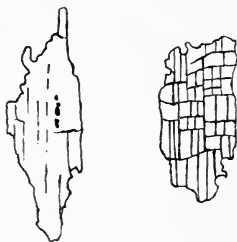


FIG. 24.—KYANITE, in Schist, North-Western Rhodesia. $\times 50$ diam.

ally. When thick enough to be coloured the pleochroism is very marked: α , dark red; β and γ , pale green to colourless. Inclusions of quartz, graphite, and magnetite are sometimes so common that the mineral is difficult to recognise, except in the variety chiasolite, which contains them arranged in a very characteristic cross-shaped fashion.

Occurs occasionally in granites, gneisses, etc., but is chiefly found in slaty rocks, altered by igneous intrusions at a considerable depth.

Kyanite, $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$. Triclinic. The hardness varies from 4 to 7 in the same crystal, according to the direction; $G = 3.6$. Unattacked by acids; decomposition rarely noticeable.

Transparent in thin sections, blue to colourless; often

somewhat clouded by inclusions. The coloured varieties show faint pleochroism, blue to colourless. Crystallizes in prismatic forms with the pinacoids strongly developed, giving hexagonal basal sections and elongated vertical ones without definite terminations. Cleavage is perfect parallel to the macropinacoid, and there is a parting parallel to the base. Frequently twinned on the macropinacoid. Cross twins, like those of staurolite, intersecting at 60° occasionally occur. Usually gives somewhat ragged lath-shaped sections. R.I. very high (1.72); double refraction moderate and negative, giving inter-

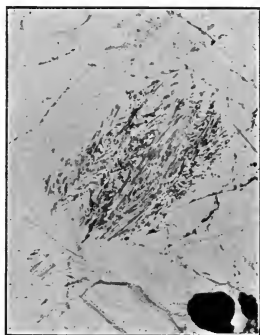


FIG. 25.—FIBROLITE ENCLOSED IN CORDIERITE. Deep green Spinel also shown. Bodenmais, Bavaria.
 $\times 30$ diam.

ference tints of the first order. Extinction in basal sections approximately parallel to the cleavage, and inclined to the twinning plane at angles up to 60° .

Both kyanite and andalusite are transformed into fibrous aggregates of fibrolite at a temperature of about 1350° , the composition remaining unchanged.

Kyanite is a characteristic mineral of many schists and gneisses in highly metamorphic regions. It is probably in all cases a product of contact alteration.

Fibrolite (*Sillimanite*). — $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$. Monoclinic. $H = 6$ to 7 . $G = 3.24$. Alters to kaolin or micaceous aggregates, but resists ordinary weathering. Chemically,

behaves like andalusite. In sections it is transparent and colourless. Always occurs as long, thin, straight prisms, usually forming fibrous aggregates. The prism angle is 97° ; cross-sections are lozenge-shaped or octagonal. The cleavage is parallel to the macropinacoid, but a cross-fracture is more characteristic, the mineral always breaking in preference to bending.

R.I. moderate; D.R. fairly strong, giving interference tints as high as blues and greens of the second order.

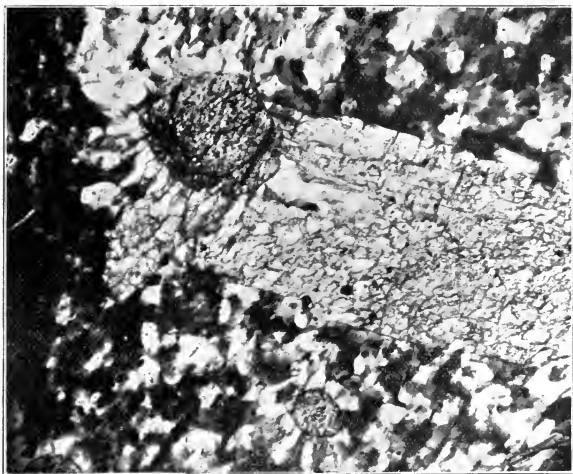


FIG. 26.—STAUROLITE, showing longitudinal and cross sections, in schist, N.W. Rhodesia. + nicols. $\times 60$ diam.

Straight extinction. Frequently occurs in contact metamorphic rocks, largely as inclusions in the other minerals, but sometimes in fibrous patches, or lenticular aggregates.

Staurolite.—Silicate of alumina, iron and magnesia, with water. Orthorhombic. $H = 7\frac{1}{2}$. $G = 3.5$. Not affected by acids, and resists weathering.

In thin sections it is colourless to yellowish, reddish, or brownish. Forms short prisms (angle 130°), bounded by a prism (110) and basal plane (001). These are occasionally

bevelled by other faces, so that it shows rectangular, lozenge-shaped, and hexagonal sections. It is often twinned parallel to (032) and (232) making curious X-shaped forms. Cleavages basal, prismatic, and parallel to the brachy-pinacoid; sometimes scarcely noticeable. When colourless the mineral is difficult to distinguish from andalusite; cross-sections are, however, generally six-sided and there is not such a perfect cleavage in longitudinal sections.

The refractive index is very high (1.75), so that the surface appears pitted. Double refraction, positive; somewhat variable, but usually moderate, seldom giving colours of the second order. Pleochroism (γ) red, (α and β) orange, not as a rule shown in thin sections.

Confined to the crystalline schists and other altered rocks around great granite masses.

Muscovite.— $\text{K}_2\text{O} \cdot 2\text{H}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$. Monoclinic. $H=2$; $G=2.8$. Sometimes contains soda. Varieties containing lithium and fluorine have been termed lepidolite and zinnwaldite. They may be recognised by their red lithium flame colouration. Muscovite is not subject to decomposition.

In sections it is transparent and colourless to light green, pinkish, or yellowish. Not pleochroic. Crystallizes in flat plates, the basal planes being the best developed faces. Basal sections are hexagonal, and vertical sections lath-shaped, showing the very perfect basal cleavage, and giving straight extinction. Frequently shows ragged edges and bent crystals.

The refractive index is exactly the same as for quartz, 1.551. Double refraction strong, negative, pinks and greens of the third order being characteristic interference tints, unless the sections are very thin. It has a brightly coloured interference figure in cleavage flakes; a cross separating into hyperbolæ on rotation.

Muscovite is found, like the preceding minerals, only under circumstances indicating great pressure. Thus, it is only present as a primary constituent in plutonic (acid) igneous rocks and in schists, gneisses, etc. The crumpled greenish variety occurring in schists is sometimes called sericite. Frequently present in clastic rocks owing to its resistance to weathering.

CHAPTER VI.

Ferro-Magnesian Minerals, etc.

BIOTITE (silicate of aluminium, magnesium, iron, and potassium). Monoclinic. $H = 2\frac{1}{2}$. $G = 2.86$. In course of decomposition, first becomes bleached, then converted into chlorite. Lenticles of calcite, chlorite, or epidote, and rhombohedra of dolomite or chalybite, frequently form between the cleavage planes in the process.

In thin sections they are yellowish, reddish-brown, or greenish to almost opaque. All the black and brown micas will here be grouped together as varieties of biotite. Absorption very strong and pleochroism very marked,

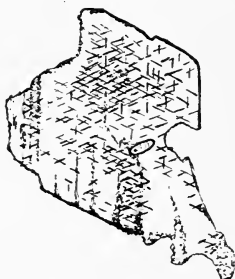


FIG 27.—SECTION OF BIOTITE, almost exactly parallel to base, showing regularly arranged inclusions of rutile needles. In granite, Sikale's Kraal, Matopos, Rhodesia. $\times 60$ diam.

some light-coloured varieties becoming almost opaque when their long axis coincides with the shorter diagonal of the polariser. The impossibility of forming biotite artificially shows its plutonic origin and accounts for the resorption border seen in many volcanic rocks. Forms well-developed hexagonal plates. Shows ragged edges less frequently than muscovite. Cleavage, basal; extremely perfect.

Analyses of Brown Micas.

	<i>Titaniferous Biotite</i> of orthophyre. Upway, Victoria. (Richards.)	<i>Lepidomelane</i> of granite. Ballyellin, Leinster. (Haughton.)	<i>Haughtonite</i> of granite. Ben Stack, Sutherland. (Heddle.)	<i>Phlogopite</i> of Pyroxene rock. Ontario, Canada. (Clarke & Sneider)
SiO ₂ ..	39.86	35.55	35.69	39.66
TiO ₂ ..	7.95	not det.	not det.	.56
Al ₂ O ₃ ..	11.13	17.08	20.09	17.00
Fe ₂ O ₃ ..	1.39	23.70	2.23	.27
FeO ..	18.10	3.55	14.01	.20
MnO ..	.58	1.95	1.00	—
CaO ..	Trace	.61	1.89	[BaO .62]
MgO ..	9.88	3.07	14.77	26.49
K ₂ O ..	6.73	9.45	7.38	9.97
Na ₂ O ..	.35	.35	.53	.60
H ₂ O, etc.	3.63	4.30	2.46	2.99
F ..	—	—	—	2.44
	<hr/> 99.60	<hr/> 99.61	<hr/> 100.06	<hr/> 100.60
			Less O = F	.94
				<hr/> 99.66

The biotite of many igneous and metamorphic rocks is often very rich in included crystals of accessories like apatite, zircon, rutile, etc. The last sometimes occurs in needles arranged in three directions along the base parallel to the edges of the hexagonal plates (see figure). The inclusions of zircon are usually surrounded by borders of a different shade to the rest of the enclosing plate, and more strongly pleochroic. These are known as "pleochroic halos," and often occur round crystals so small as otherwise to pass unnoticed. Joly and Mügge have ascribed these halos to the alteration of the surrounding biotite substance owing to the radio-activity of the zircon. If this explanation be correct, orthite, which always contains thorium and probably also uranium, should show similar effects, and as a matter of fact it does in many Rhodesian granites. The halos are usually more sharply marked off from the enclosing biotite than those round zircon, and it is curious that in some cases the larger orthite crystals do not show any halos, though the small ones in the same slice do.

The refractive index is low, 1.5. D.R. strong and negative, bright colours of the second order showing when the absorption is not too great. Basal sections are practically isotropic. Often gives an apparently uniaxial figure in convergent light.

Occurs in many igneous rocks and is also a characteristic product of thermal metamorphism.

The *Hornblende*, or amphibole group, are silicates of iron, magnesia, lime, alumina, etc., crystallising in the oblique prismatic system. $H = 5\frac{1}{2}$. $G = 3.2$. Not attacked by acids. The amphiboles are lower in specific gravity and more strongly magnetic than the corresponding pyroxenes. Alteration to chlorite is frequently seen, while weathering resolves them into a mixture of car-



PLEOCHROIC HALOS IN BIOTITE.

FIG. 28.—Ordinary type of circular halo round zircon breadth about .035 mm. In granite of Matopo Hills, Rhodesia.

FIG. 29.—Halo, with dark rim, round orthite (allanite). In granite, north of Kahlele's Kraal, Matopo Hills, Rhodesia.

FIG. 30.—Halos round group of zircon crystals. In granite of Sea Point, Capetown.

× 100 diam.

bonates, iron hydrate, etc.; serpentine and talc appear also to result at times from the alteration of hornblende.

Hornblende is rarely perfectly transparent and colourless. In thin sections it is sometimes yellow or blue, but generally green or brown. The absorption is strong and the pleochroism is very marked in most cases, even with varieties which are almost colourless when viewed in natural light. Absorption and colouration are strongest when the long axis of the crystal is parallel to the short axis of the lower nicol. The perfectly colourless variety is termed tremolite; the green fibrous, or blade-like variety actinolite; the blue, soda-bearing varieties, crocidolite riebeckite and glaucophane; the deep brown lustrous variety, black by reflected light, basaltic hornblende. A

supposedly right-prismatic amphibole has been called anthophyllite. Hornblende, pseudomorphous after augite, is known as uralite. Hornblende is evidently a mineral requiring great pressure for its formation. Hence it is comparatively rare in the lavas, and when it occurs is frequently surrounded by a resorption border, due to corrosion consequent on the relief of pressure when poured out at the surface. The brown varieties may be confidently regarded as original; the green varieties, except in the acid igneous rocks, are generally secondary. Common hornblende is green or brownish, and forms short prismatic crystals, sometimes terminated by clinodomes, or by pyramid faces and basal planes. Terminations are

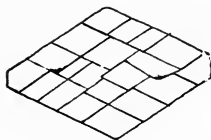


FIG. 31.—CROSS SECTION OF HORNBLENDE,
showing cleavage traces.

frequently wanting, even when the prism faces are well developed. The acute angles of the prisms are frequently truncated by clino-pinacoids. The prism angle is 124° . Cleavage perfect parallel to the prism faces. Transverse sections are lozenge-shaped or six-sided. Vertical sections are somewhat similar, but elongated in the direction of the vertical axis, as indicated by the cleavage, which gives only one set of traces in this direction. Sometimes twinned on the ortho-pinacoid; twinning is not common, however. Skeleton crystals, and even microlites are rare, as might be expected from its usual deep-seated origin. They occur, however, in the well-known Arran "pitchstone." Zoning is not common, but crystals are sometimes differently coloured in different parts.

Analyses of Amphiboles.

	<i>Brown Hornblende from Andesite, Siebengebirge (Rosenbusch.)</i>	<i>Basaltic Hornblende from Basalt, Bilin, Bohemia. (Stanley.)</i>	<i>Hornblende Grenville, Quebec. (Stanley.)</i>	<i>Colourless Hornblende from cryst, Limestone. Ceylon. (Hancock.)</i>
SiO ₂ ..	39.29	39.95	45.79	47.04
TiO ₂ ..	4.86	1.68	1.20	—
Al ₂ O ₃ ..	16.57	17.58	11.37	13.76
Fe ₃ O ₃ ..	9.18	7.25	.42	Trace
FeO ..	3.19	2.18	.42	—
MnO ..	—	Trace	.39	—
CaO ..	12.90	11.96	12.71	13.39
MgO ..	10.40	14.15	21.11	21.26
K ₂ O ..	Not det.	1.98	1.69	—
Na ₂ O ..	Not det.	3.16	2.51	4.01
H ₂ O ..	Not det.	.54	.67	.60
F ..	Not det.	.03	2.76 [Graphite.30]	
	<hr/> 96.39	<hr/> 100.46	<hr/> 101.04	<hr/> 100.36
Less O = F		.01	1.16	
		<hr/> 100.45	<hr/> 99.88	

R.I. fairly high (1.64); D.R. strong; giving rise to interference tints of the second order. These are frequently masked by the strong absorption. The extinction angle ranges in the different amphiboles from about 5°, in the blue soda-bearing varieties to about 25° in brown hornblende.

The amphiboles are very abundant in the igneous and metamorphic rocks. Tremolite and actinolite are always the result of changes, brought about largely by pressure, and all the varieties found in the igneous rocks seem to have been formed under deep-seated conditions, even when occurring in the lavas.

TABLE OF PYROXENES AND AMPHIBOLES.

	<i>Pyroxenes.</i>		<i>Amphiboles.</i>
Right-Prismatic (Rhombic) ...	Enstatite and	...	Anthophyllite,
	Hypersthene	...	Gedrite
Oblique-Prismatic (Monoclinic)...	Diopside and	...	Tremolite &
	Augite	...	Hornblende
Soda-bearing varieties ...	Aegirine and	...	Riebeckite &
	Acmite	...	Glaucophane
Altered forms ...	Diallage	...	Actinolite

Augite (Monoclinic Pyroxene) has a composition similar to hornblende. H from 5 to 6. G from 3.3 to 3.55. Under the influence of dynamic metamorphism it readily alters into a fibrous variety of hornblende, known as urallite, which sometimes, though rarely, retains the crystalline form of the augite. Alters to chlorite, carbonates, etc., and (under deep-seated conditions), sometimes changes to serpentine.

Transparent and colourless, as a rule, in slices: sometimes, however, in intermediate rocks, it has a greenish

tinge, and a faint brown shade is common in basalts and dolerites. In certain ultrabasic rocks it has a distinctly pink tint, while a faint purplish brown is a very characteristic colour of the varieties occurring in highly alkaline rocks. The colourless varieties have been called diopside; while an altered variety occurring in many gabbros is known as diallage. The colours in thin section are generally very much lighter than those of the related amphiboles, from which they are further distinguished by the absence of pleochroism in almost all cases. The yellowish-green and purplish-brown varieties are the most pleochroic, but even these are only slightly so; the ordinary greyish and brownish kinds are not pleochroic at all.



FIG. 32.—AUGITE. Longitudinal Section, showing hour-glass Zoning. $\times 40$ diam. In nepheline dolerite of Lobauer Berg, Saxony.

Augite usually occurs in short stout crystals bounded by the prism, with ortho- and clino-pinacoids, and terminated by pyramidal faces. In some of the basic volcanic rocks the prisms are more elongated, and the basal plane is also developed. Irregular plates and granules are likewise found. Often twinned on the ortho-pinacoid; lamellar twinning is sometimes seen. Zoning is fairly common, a characteristic hour-glass structure being sometimes shown. Cleavage is fairly perfect parallel to the prism (angle 87°); sometimes also parallel to the pinacoids. Basal sections

are octagonal and crossed by a grating of nearly rectangular cleavage traces. Vertical sections are usually four or six-sided, parallel in the latter case to the orthopinacoid.

The refractive index is high (1.68), the surface of a section looking perceptibly rough. The double refraction is strong, slightly greater than for hornblende. The interference tints are of the second order, and are little obscured by absorption, unlike hornblende. The extinction angles of the oblique-prismatic (monoclinic) pyroxenes are high—much higher than those of the corresponding amphiboles. Measured to the parallel cleavage traces in longitudinal sections they commonly reach 45° or more in common augite. In the deep green, soda-bearing variety aegirine, however, they are very small—not more

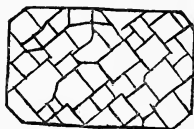


FIG. 33.—CROSS SECTION OF A PYROXENE CRYSTAL, showing cleavage traces.

than 2° or 3° . At the same time, in all ordinary cases, a very oblique extinction characterises the species.

Augite is of very common occurrence in the igneous rocks, especially in the intrusive and volcanic types.

Enstatite (Rhombic Pyroxene), MgO SiO_2 , is very similar in composition to augite and hornblende. It crystallizes, however, in the orthorhombic system. H = from $5\frac{1}{2}$ to 6; G = 3.1 to 3.5. Not attacked by acids except hydrofluoric and hydrofluosilicic. It readily alters to a fibrous variety of serpentine (known as bastite), and sometimes to hornblende; also to aggregates of limonite, etc.

It is clear and colourless to brown, the colour, pleochroism, hardness and specific gravity increasing with the percentage of iron. Some writers distinguish four varieties:—Enstatite proper, with not more than 5 per cent. of iron oxide (FeO); bronzite, with from 5 to 15 per cent.; hypersthene, with 15 to 25 per cent.; and amblystegite, with more than 25 per cent. For all ordinary purposes, however, it seems quite sufficient to distinguish the less ferriferous and only slightly pleo-

chroic varieties as enstatite, and the more ferri-ferous highly-coloured and pleochroic varieties as hypersthene (10 per cent. or more of FeO). When idiomorphic, enstatite has outlines much resembling those of augite, but often shows pinacoidal cleavages. The prism angle is 92° . None of the cleavages are very well developed, however, and irregular cracks are common. Regularly arranged enclosures occur. Twinning is very rare. Enstatite is sometimes intergrown with augite, forming a core to it, or making a kind of micropegmatite. The "basal striation" and "herring-bone" structure sometimes seen in augite appear to be due to inclusions of enstatite.

The refractive index is high, 1.67; double refraction weak, only just exceeding quartz. The most ferri-ferous varieties give interference tints up to yellow and red of the first order. This affords a useful means of distinction from augite, hornblende and olivine, which it in some cases closely resembles. The extinction is straight in longitudinal sections.

Enstatite occurs abundantly in certain igneous rocks, especially in andesite and other basic varieties; also in meteorites.

Analyses of Pyroxenes.

	<i>Augite</i> from dolerite of Valmont, Colo., U.S.A. (Eakins.)	<i>Augite</i> from granite of Silver Cliff, Colo. (Eakins.)	<i>Chrome Diopside</i> Colossus Diamond Mine, Rhodesia. (Mennell.)	<i>Aegirine</i> from volcanic breccia, Port Chal- mers, N.Z. (Marshall.)	<i>Hyper- sthene</i> ortho- phyre of Upway, (Vic.) Australia. (Richards.)
SiO ₂ ..	49.10	48.72	53.93	49.10	50.42
Al ₂ O ₃ .	7.95	9.27	1.90	1.46	3.51
Fe ₂ O ₃ .	—	3.77	5.97	25.14	4.06
			Cr ₂ O ₃ .70		TiO ₂ 2.01
FeO ..	8.30	6.34	2.67	9.26	23.54
MnO .	—	.34	—	—	.24
MgO .	12.37	14.67	20.08	.13	13.04
CaO ..	22.54	16.79	13.11	2.95	1.30
K ₂ O ..	Trs	—	—	1.79	.69
Na ₂ O .	Trs	.19	—	8.11	—
H ₂ O ..	—	.18	1.63	—	.16
					P ₂ O ₅ .92
	100.26	100.27	99.99	97.94	99.98

Olivine $2\text{MgO}.\text{SiO}_2$. Orthorhombic. $H = 6\frac{1}{2}$; G up to 3.4. Is attacked by hot hydrochloric acid with separation of gelatinous silica. Readily alters to serpentine along cracks. In the older olivine-bearing rocks the mineral is frequently completely converted into serpentine pseudomorphs, whose origin may be generally recognised by their characteristic micro-structure.

When unaltered it is always clear and colourless in sections. By reflected light it is greenish-yellow; a greenish tint is also produced by alteration. A few unaltered ferriferous olivines ("fayalite" and "hyaloseridite") are yellowish or brownish.

The crystalline form and cleavage are, as a rule, poorly developed in rocks, although the mineral is an early product of consolidation. A few fine sharp cleavage cracks may, however, generally be found on close examination. Microlites, skeleton crystals, and twins are very rare. When good crystals are found they are often bounded by a large number of faces, the pinacoids being predominant. Rounded grains or granular aggregates are also characteristic. Generally traversed by irregular cracks, which are frequently rendered more conspicuous by the development of secondary magnetite, or by incipient alteration of the adjacent olivine into serpentine.

The refractive index is high (1.68), the surface always appearing quite rough or pitted under the microscope, in slices which have not been very highly polished. Double refraction, very strong, slices giving interference tints of the second and third orders even when quite thin. Gives straight extinction in sections from the prism zones, but the strong dispersion causes oblique extinction in unsymmetrical sections.

Olivine is abundant in the igneous rocks, being characteristic of the basic division. It is also a frequent constituent of meteorites, and occurs in contact altered limestones and dolomites (Forsterite).



FIG. 34. — OLIVINE CRYSTAL.
From Spiegel
River Picrite.
 $\times 60$ diam.

ADDENDUM.

The distinction of augite and hornblende sometimes presents difficulties. The cleavage angles are characteristic if they can be observed, and sections shewing the two sets of cracks crossing one another should be sought. Augite is seldom coloured deeply, and is hardly ever strongly pleochroic. A coloured hornblende always exhibits marked pleochroism, while an augite, even of the same colour, never shews it to the same degree. The extinction angles, too, are quite different; if longitudinal sections are taken, as indicated by the outline, and the presence of only one set of parallel cleavage traces, hornblende usually extinguishes at a maximum angle of 18° , some of the commonest varieties having a maximum of 12° , while 22° is about the limit for ordinary occurrences. Few augites, on the other hand, have as low an angle as 36° , and those most commonly occurring give an approximation to the maximum possible angle of 45° (that is, of course, if direction be not taken into account).

Augite and olivine are often confused, and epidote is liable to be mistaken for either. The last is an alteration product, and need not be suspected in a perfectly fresh-looking rock, except in certain granulites and allied types. In the absence of good cleavage, the similarity of refractive index and double refraction makes fresh olivine resemble augite very closely. If cleavages are sought for carefully, they are generally to be found, however, those of olivine being indicated by finer and sharper lines than in the case of augite. The straight extinction of olivine may be noted, and in any but very fresh rocks the production of serpentine along cracks at once distinguishes olivine. If necessary, chemical methods may be employed; olivine is readily attacked by acids, while augite is unaffected. Epidote is generally somewhat yellow, at least in patches, and is then quite markedly pleochroic. Its double refraction is also somewhat higher than that of either of the previous minerals.

Enstatite may be overlooked when in company with augite owing to its similarity of appearance. Its weak double refraction and straight extinction may suffice for its identification, and it is frequently faintly, but distinctly

pleochroic, often in shades of pink and green. Cross-sections give a positive bisectrix in convergent polarised light, the axial angle being 92° . Corresponding sections of augite shew a single optic axis. Longitudinal sections of augite, parallel to the ortho-pinacoid, which are deceptive on account of their low extinction angles and weak double refraction, may be distinguished by their giving an optic axis.

CHAPTER VII.

Miscellaneous Accessory and Secondary Minerals.

APATITE, $\text{Ca}_3(\text{PO}_4)_2$, with some fluoride or chloride of calcium. Hexagonal. $H = 5$; $G = 3.2$. Readily soluble in hydrochloric acid, the solution giving a yellow precipitate with ammonium molybdate. Not susceptible to ordinary weathering, remaining quite fresh even in very decomposed rocks.

Clear and colourless in slices, or occasionally with a faint bluish tinge. Forms hexagonal prisms terminated by basal planes, or by pyramid faces, or by a combination of the basal plane with the hexagonal pyramid. The prisms are sometimes short and stout, but often, especially in the more basic igneous rocks, long and slender. More or less

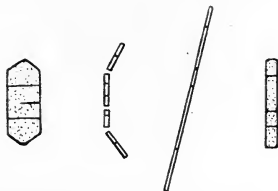


FIG. 35.—APATITE CRYSTALS IN LONGITUDINAL SECTION. $\times 60$ diam.

rounded granules are also common in the plutonic and metamorphic rocks. The cleavage parallel to the base is seldom observed; a cross fracture is, however, very common. Never twinned; very rarely zoned.

The refractive index is high (1.64); double refraction very weak, giving neutral tints or white of the first order. Straight extinction; in convergent light gives a cross without rings.

Apatite is one of the most widely-distributed minerals, occurring in nearly all igneous and metamorphic rocks; it is particularly abundant in certain dolerites, syenites, and diorites.

Sphene (*Titanite*), $\text{CaO} \cdot \text{SiO}_2 \cdot \text{TiO}_2$. Monoclinic. $H = 5$ to $5\frac{1}{2}$; $G = 3.5$. Is attacked by sulphuric acid, the solution giving an orange colouration with hydrogen peroxide. After fusion with sodium carbonate dissolves in hydrochloric acid, the solution turning pale violet after boiling with tin-foil and being allowed to cool.

In sections is colourless, yellow, pinkish, or brown, to opaque white, but most often yellowish-brown. Not very transparent as a rule. Forms crystals giving characteristic acute lozenge-shaped sections; also frequently granular. The absorption is greatest when the length of a section is at right angles to the shorter diagonal of the lower nicol. Sometimes, though rarely, twinned.

The refractive index is extremely high (1.91). The double refraction is also extremely strong, the interference tints reaching into the greys of the high orders. Brighter colours are often masked by the strong absorption. Sphene is not found as a primary constituent of the basic rocks, but frequently occurs as an alteration product of ilmenite or of titaniferous magnetite. It is widely distributed as an accessory in the more acid plutonic and metamorphic rocks, being especially abundant in the syenites and diorites.

Orthite (*Allanite*), is a silicate of calcium, aluminium, cerium, iron, thorium, lanthanum, didymium, yttrium, and erbium, crystallizing in the monoclinic system. $H = 5\frac{1}{2}$; $G = 3.9$. Decomposed by boiling hydrochloric acid. Not markedly affected by weathering as a rule.

In thin sections the colour is deep brown to yellowish or orange. Sometimes rather strongly pleochroic, changing from light yellowish or greenish-brown to dark brown, but in most cases pleochroism is feeble or *nil*. Forms



FIG. 36.—SPHENE CRYSTAL.
× 30 diam.

crystals, often of considerable size for a rock-former, somewhat elongated parallel to the orthopinacoid, and similar to those of epidote, with which it is frequently intergrown, always forming a core surrounded by the epidote. Does not usually show good cleavages; sometimes twinned on the orthopinacoid and often zoned.

The refractive index is high (1.78), the double refraction is very variable: sometimes quite strong, but more commonly weak; may be perfectly isotropic; sign variable.

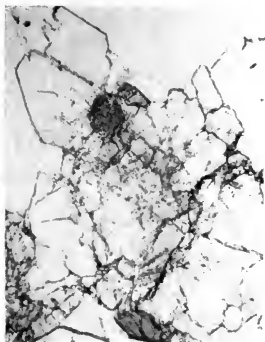


FIG. 37.—ORTHITE, enclosed in Epi- FIG. 38.— ORTHITE, enclosed in
dote, which is surrounded by Biotite. Epidote of Crystalline Limestone
In granite of Jibuyi River, N.W. of Donegal, Ireland. $\times 25$ diam.
Rhodesia. $\times 50$ diam.

Orthite occurs as an accessory in granites, and more rarely in other igneous rocks; also in granulites and amphibolites, and in sandstones derived from their disintegration. It is probably much commoner than is generally recognised.

Perovskite, CaO.TiO_2 . Regular. $H = 5\frac{1}{2}$; $G = 4.1$. Not attacked by acids except hot concentrated H_2SO_4 .

It is usually colourless and but slightly transparent, occurring in octahedra, cubes, etc., but more often in irregular grains. In general appearance is very similar to sphene.

The refractive index is extremely high (2.38). It usually shows anomalous double refraction, with twin lamellæ like those of leucite. Perovskite occurs as an accessory in ultra-basic lavas and dyke-rocks, especially those containing melilite, in which it may be very abundant.

Zircon, ZrSiO_4 . Tetragonal. $H = 7\frac{1}{2}$ $G = 4.5$. Not attacked by acids or affected by weathering. Fused with carbonate of soda the silica is removed and the ZrO_2 is left in minute hexagonal plates.

Colourless or of pale tints, and always in crystals; usually very perfect, short, four-sided prisms, with pyramidal terminations. It is sometimes zoned, but there is no noticeable cleavage in sections.

The refractive index is extremely high (1.99); double refraction extremely strong, producing interference tints of the third or higher orders in the thinnest sections.



FIG. 39.—ZIRCON CRYSTALS, isolated from the Matopo Granite.

Sparingly but widely distributed in rocks of all classes—igneous, aqueous, and metamorphic.

Cordierite (Iolite), $2\text{MgO} \cdot 2\text{Al}_2\text{O}_3 \cdot 5\text{SiO}_2$. Orthorhombic. $H = 7$; $G = 2.6$. Almost infusible before the blow-pipe, and practically insoluble in ordinary acids. Treated with hydrofluosilicic acid yields prismatic crystals of magnesium fluosilicate. Alters to yellowish micaceous aggregates known as pinite, etc.

Transparent and colourless in thin slices; in thicker plates yellowish, bluish and violet. When coloured it is strongly pleochroic. It is sometimes in crystals, showing the prism, brachy-pinacoid and basal plane. The prism angle is 119° , so that in the combination the mineral looks like a hexagonal one. It is sometimes twinned on the prism face, trillings being characteristic. The cleavage parallel to the brachy-pinacoid is seldom noticeable. Longitudinal sections are rectangular, transverse sections hexagonal.

R.I. low (1.54). The double refraction is weak and negative; interference tints are the same as for quartz. Pleochroism is not noticeable in rock slices, except sometimes round inclusions. The latter are frequent in metamorphic rocks, but may be altogether absent in volcanic rocks. In its physical and optical properties it resembles quartz so closely that it can often be identified only by chemical means, or by its biaxial interference figure. Twin individuals extinguish at an angle of 60° to each other in basal sections; in longitudinal sections they extinguish straight, but give different interference tints during rotation.

Cordierite occurs in contact rocks, and, by derivation of material from them, in a few granites, etc.

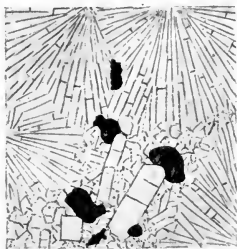


FIG. 40.—TOPAZ, from altered tin-bearing granophyre of Watsonville, Queensland. $\times 40$ diam.

Topaz, $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$, with some fluorine. Orthorhombic. $H = 8$; $G = 3.5$. Not affected by acids. Sometimes found altered to kaolin or muscovite, but is little affected by ordinary weathering.

Transparent and colourless in slices. When crystallized forms combinations of one or more prisms with the ortho-dome and pyramid; sometimes found in more or less rounded granules. The cleav-

age is basal and perfect, the flakes showing good interference figures.

The refractive index is fairly high (1.62), the surface appearing somewhat rough; double refraction weak, interference tints being about the same as for quartz.

Topaz occurs in certain granites and granophyres, as at Meldon, in Devonshire, the Mourne Mountains, Ireland, and in Tasmania, Queensland, New South Wales, Rhodesia, Saxony, and Brazil.

Beryl, $3\text{BeO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2$. Hexagonal. $H = 7\frac{1}{2}$; $G = 2.7$. Not attacked by acids. Unaffected by weathering as a rule.

Transparent and colourless in slices. Crystallizes in

hexagonal prisms seldom showing good terminations. Cleavage, imperfect, basal; the flakes show a good uniaxial figure in convergent light.

R.I. low (1.58). D.R., weak, negative; interference tints being lower than for quartz.

Beryl occurs in somewhat similar situations to topaz among certain granites, granophyres, pegmatites, etc. It also sometimes appears as a contact mineral in schists and crystalline limestones.

Pyrites, FeS_2 . Regular. $H = 6$; $G = 5$. Not attacked by hydrochloric acid, but soluble in nitric acid with separation of sulphur. Before the blow-pipe gives a sulphurous smell and turns black. Readily alters by oxidation into haematite or limonite.

Opaque even in the thinnest slices; by reflected light pale metallic yellow. Forms cubes, octahedra, etc., but is sometimes granular or massive.

The refractive index is extremely high; the surface appears very rough, and has a brilliant lustre. Pyrites is widely distributed as a secondary product in many igneous, metamorphic, and stratified rocks.

Pyrrhotine, FeS . Hexagonal (?) $H = 4$; $G = 4.5$. Readily soluble in hydrochloric acid with evolution of sulphuretted hydrogen. In powder it is sometimes magnetic.

Always opaque; by reflected light it is tin white to bronze yellow, with a rather dull metallic lustre. Always occurs in irregular granules. The refractive index is very high.

It occurs as a secondary product in certain basic rocks; highly characteristic of ore deposits near igneous contacts.

Copper Pyrites, CuFeS_2 . Tetragonal. $H = 3\frac{1}{2}$; $G = 4.2$. It is soluble in hydrochloric acid, and gives a green colour to the blow-pipe flame. Before the blow-pipe it colours the borax bead opaque red in the reducing flame, and green in the oxidising flame. Readily scratched by a knife.

Quite opaque; by reflected light it is very bright yellow, and its lustre is brilliantly metallic. Often surrounded by greenish alteration products. Compared with ordinary pyrites the colour is much more pronounced. Forms irregular grains and patches.

Occurs as a secondary mineral in certain diorites, granites, granophyres, and many other igneous and metamorphic rocks, particularly those containing hornblende, also among sediments once rich in organic matter.

Tourmaline is a boro-silicate of aluminium, magnesium, iron, etc. Hexagonal. $H = 7$; $G = 3.2$. Not attacked by any acids, nor is it susceptible to alteration.

Transparent: rarely colourless, usually blue, or yellow, to deep brown; occasionally green or pink. Occurs in hemimorphic crystals; hexagonal or trigonal prisms are the dominant forms, often giving heart-shaped or hexagonal sections; vertical sections are usually elongated,



FIG. 41.—TOURMALINE, from edge of granite, Cape Town. Granular zoning. $\times 40$ diam.

and the crystals sometimes acicular. Often granular. Zoning in different colours is frequent and very characteristic. The absorption is strongest when the length of section is perpendicular to the shorter diagonal of the polarising prism, the pleochroism being very marked (nearly or quite colourless to deep brown in extreme cases).

The refractive index is fairly high (1.63). The double refraction is strong and negative, but the interference tints are often masked by the strong absorption. Extinction is straight. Transverse sections give a cross in convergent polarised light, which sometimes breaks upon rotation.

Tourmaline occurs along the margins of many granites, etc., apparently as an alteration product by acid vapours. It is also found in rocks altered by contact metamorphism, and by derivation from them in the clastic sedimentary rocks.

Fluor, CaF_2 . Regular. $H = 4$; $G = 3.2$. Soluble only in sulphuric acid, with evolution of hydrofluoric acid, which may be made to etch glass.

Clear and colourless, blue, or violet. The colour is often irregularly distributed, and coloured varieties lose their colour on heating to redness. Does not occur in crystals as a rock-former.

The refractive index is very low (1.43). Isotropic. Occurs as a secondary mineral in a few granites, etc.; also in certain limestones and marbles.

Kaolin, $\text{Al}_2\text{O}_3 \cdot (\text{SiO}_2)_2 \cdot 2\text{H}_2\text{O}$. Monoclinic. Very soft. $G =$ about 2.5. Decomposed by boiling sulphuric acid.

Usually found in minute granules, nearly opaque, but among these occasionally occur six-sided crystalline plates, bounded by prism, clino-pinacoids, basal planes, and orthodomes. Sometimes twinned on the ortho-pinacoid. Cleavage is usually parallel to the ortho-pinacoid and base.

The refractive index is low and the double refraction strong, but the individual grains are usually too small for this to be perceptible in ordinary rock sections, where it appears in cloudy patches. Kaolin is frequently found as a decomposition product of aluminous silicates.

Serpentine, $3\text{MgO} \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$. Monoclinic (?) $H = 3$; $G = 2.6$. Readily attacked by either HCl or by H_2SO_4 , leaving a gelatinous residuum of silica.

Transparent and colourless, greenish, yellow, brown, etc. Occurs in more or less fibrous aggregates, frequently forming pseudomorphs after olivine, etc. The refractive index is low (about 1.5). The double refraction may be considerable, but the mineral sometimes appears almost isotropic. Its derivation is generally well indicated by its micro-structure. When formed from olivine it shows a characteristic "mesh-structure," alteration having first proceeded along the intersecting cracks in the olivine. When produced from enstatite it forms parallel fibrous aggregates known as "bastite." The alteration of

hornblende and augite gives rise to serpentines whose fibres frequently follow the cleavage planes of the original minerals.

Serpentine occurs as an alteration product of the minerals referred to, also in large masses resulting from the complete alteration of the more basic rocks.

Talc, $3\text{MgO} \cdot 4\text{SiO}_2 + \text{H}_2\text{O}$. Orthorhombic. $H = 1$; $G = 2.8$. Not acted upon by acids. Heated before the blow-pipe with cobalt nitrate becomes pink.

In slices transparent and colourless. Occurs in flat plates without definite form, usually as scaly aggregates. There is a perfect cleavage parallel to the base. Extinction is parallel to the cleavage traces.

The refractive index is low (1.55), exactly equal to that of quartz. Double refraction very strong, giving rise to interference tints of the third order; it is often obscured by overlapping of the flakes.

It occurs almost exclusively in rocks which owe their characters to the combined action of thermal waters and dynamo-metamorphism.

Chlorite.—Under this head are included a number of secondary minerals, agreeing in many important respects, but differing considerably in composition, etc. Monoclinic. $H = \text{about } 2\frac{1}{2}$; G varies from 2.7 to 3. The chlorites gelatinise with sulphuric acid; aluminium, iron, and magnesium can be detected in the solution.

They are generally green in colour, or nearly colourless; but sometimes almost opaque. The chlorites occur in fibrous scaly aggregates; also in hexagonal plates, or often pseudomorphous after biotite, hornblende, etc. The cleavage is basal, perfect. Very seldom twinned.

In the *Pennine* varieties the refractive index is low, being 1.57. The double refraction is very weak, basal sections being almost isotropic. A peculiar deep blue of the first order is a characteristic interference colour of pennine. The extinction is parallel to the cleavage traces. *Clinochlore* has stronger double refraction, with interference tints equal to those of quartz. Pleochroism from green to yellow or brown.

Chlorite is a frequently occurring alteration product in igneous rocks, and an important constituent of many schists.

Chloritoid (*Ottrelite*). Hydrated silicate of aluminium, iron, magnesium, manganese, etc. Triclinic. $H = 6\frac{1}{2}$; $G = 3.5$. Under this name are included what are probably more than one species whose properties have not been determined with certainty. Not attacked by acids.

May be clear and colourless, or greenish, and not very transparent. The pleochroism is generally green to blue. Crystals give four or six-sided sections, the base being the best developed face, and the direction of elongation parallel to it. Often lath-shaped, with ragged terminations, lenticular or granular. Twinning parallel to the base is fairly common, and frequently lamellar. Concentric or hour-glass zonal structures are sometimes seen. The basal cleavage is at times well developed; and other cleavages are sometimes observed. Irregular cracks and fractures often seen, and inclusions are very common, often rendering the crystals almost opaque, though certain occurrences are quite free from them.

R.I. high (1.72). The double refraction is weak, scarcely higher than for quartz.

Chloritoid is found in certain phyllites, etc., and in sandstones or conglomerates, of which the argillaceous matrix has been altered by pressure, *e.g.*, the Rand "Banket."

Epidote.—Silicate of calcium, aluminium, iron, hydrogen, etc. Monoclinic. $H = 6\frac{1}{2}$; $G = 3.4$. Not attacked by acids.

Transparent and colourless, or pale yellow; more rarely pale green or pink. Except in veins it is seldom well crystallized, and is usually granular; the crystals give lath-shaped and six-sided sections. The perfect basal cleavage is not, as a rule, well seen in sections.

Refractive index very high (1.76). Double refraction extremely strong; interference tints being of the third order in the thinnest sections. Pleochroism is generally

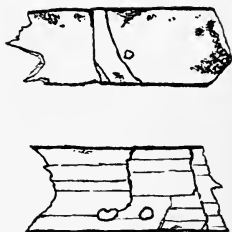


FIG. 42.—CHLORITOID, in Rand "Banket." Sections parallel and perpendicular to the base. $\times 60$ diam.

weak, or not noticeable; sometimes it is yellow for rays parallel to the long axis, and green to colourless for rays vibrating at right angles to this axis; in the red manganese-bearing varieties (*e.g.*, piedmontite), red to colourless or yellow. Extinction is straight.

It occurs as an alteration product in igneous rocks, and is often present in metamorphic ones, especially the granulites. May possibly be a primary constituent of certain granites.

Zoisite has a composition similar to that of epidote, but crystallizes in the orthorhombic system. $H = 6\frac{1}{2}$; $G = 3.8$. It is not attacked by acids.

Transparent and colourless. The manganiferous variety,

thulite, is red and pleochroic. Microlites commonly show prism faces and the brachy-pinacoid, and occur often in parallel groups; cross-sections are, therefore, usually six-sided, while longitudinal ones are lath-shaped and sometimes terminated by domes. Good crystals are, however, uncommon. Cleavage perfect, parallel to the brachy-pinacoid, *i.e.*, to the length of microlites. Cross-fracture characteristic, parallel to the base.

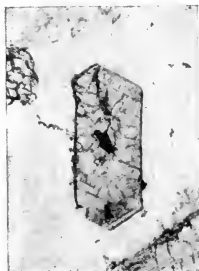


FIG. 43.—EPIDOTE CRYSTAL, from Crystalline Limestone of Donegal, Ireland. $\times 30$ diam.

R.I. very high (1.70). Double refraction very low; even in thick sections does not show interference tints higher than grey of the

first order. These two characters, together with the straight extinction, afford an excellent means of determination, though apatite is very similar in these respects.

Zoisite is of fairly frequent occurrence in rocks which have been subjected to contact metamorphism or to alteration under considerable pressure. It is frequently associated with epidote.

Barytes, $BaSO_2$. Orthorhombic. $H = 3$; $G = 4.5$. Clear and colourless in sections. Forms irregular plates. Cleavage prismatic.

R.I. high (1.64). D.R. weak, giving interference tints up to first order yellow. $\rho < \nu$.

Occurs as a cementing material in certain sandstones.

Gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. Monoclinic. $H = 2$; $G = 2.3$. Dissolves slowly in hydrochloric acid.

Transparent and colourless. Forms small fibrous prisms, large plates, or occurs in granules. Twinning parallel to the ortho-pinacoid. Cleavage very perfect parallel to the clino-pinacoid, and fairly perfect parallel to the prism faces. Liquid enclosures are common; also inclusions of iron oxide, etc.

R.I. low. Double refraction negative and weak, being exactly equal to that of quartz.

Gypsum occurs as a distinct rock, usually associated with rock-salt, as in the English Trias, the French Tertiary beds, and in the recent deposits of Western Australia; also as a cementing material of certain sandstones.

Opal, $\text{SiO}_2 \cdot \text{H}_2\text{O}$. Amorphous. $H = 6$; $G = 2.1$. Soluble in caustic potash or soda.

In sections is transparent and colourless. Forms irregular concretionary masses and fills amygdulæ and decomposition cavities or acts as a cementing material.

R.I. very low (1.45). Isotropic in some occurrences, but many show anomalous double refraction, so that the mineral much resembles chalcedony.

Occurs as a secondary product in many igneous rocks, and forms the bulk of certain sinters, besides being occasionally found as a cementing material in sandstones (e.g., at Taba-s' Induna, near Bulawayo).

Calcite, CaCO_3 . Rhombohedral. $H = 3$; $G = 2.72$. It is readily soluble in acetic acid or cold hydrochloric acid, crystals of gypsum forming on addition of sulphuric acid.

Colourless in slices, but owing to the strong absorption does not look quite clear. Never found in crystals as a rock-former, though sometimes in spherical concentric or radiating aggregates. Cleavage extremely perfect, rhombohedral, the sharply-defined cleavage traces being characteristic. Lamellar twinning is very common.

R.I. low (1.6). D.R. negative and extremely strong, so that definite colours of the lower orders are not recognisable as a rule; greenish-white is the most usual, but green

and pink of a high order are sometimes seen. Basal sections give a cross with many coloured rings in convergent polarised light. Differences of relief are very marked on rotation over the polariser.

Forms large sedimentary and metamorphic rock masses (limestones and marbles), and is also frequently found as the cementing material of sandstones. Very common as a decomposition product in the more basic igneous rocks, and the hornblende and chlorite schists.

Dolomite, $(\text{MgCa})\text{CO}_3$. Rhombohedral. $H=3\frac{1}{2}$; $G=2.9$.

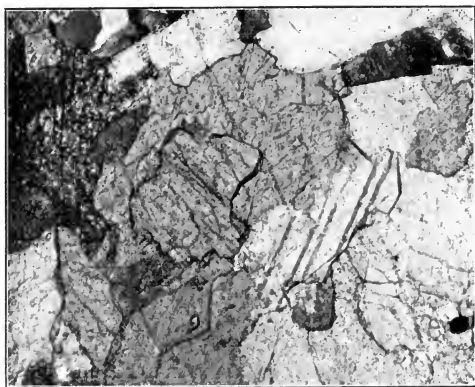


FIG. 44.—CALCITE AGGREGATE. + nicols.

Does not effervesce with cold hydrochloric acid; dissolves, however, in the boiling acid. From fluosilicate and other solutions, characteristic crystals of struvite $(\text{NH}_4\text{MgPO}_4 \cdot 6\text{H}_2\text{O})$ can be obtained by the addition of NH_3 (and AmCl) till alkaline, and then further adding a drop of sodium phosphate. The crystals form best in dilute solutions and in the cold.

Similar to calcite in most respects, showing the characteristic cleavage and strong absorption of the rhombohedral carbonates. Unlike calcite, frequently occurs in crystals, the fundamental rhombohedron ($R\pi$) being the

only common form. Like magnesite, it never shows the lamellar twinning so often seen in calcite.

The refractive index and (negative) double refraction are much the same as for calcite. Curved faces and cleavage traces are frequently observed and highly characteristic.

Forms rock masses of sedimentary origin. Sometimes occurs in other rocks as a decomposition product, especially in company with serpentine, talc, etc.

Garnet.—Regular. $H = 7$; $G = 3.5$. The members of the garnet group vary considerably in composition owing to the replacement of isomorphous bases by one another, but all varieties crystallize in the regular system in forms in which the dodecahedron is dominant. Not affected by acids, or by the processes of weathering.

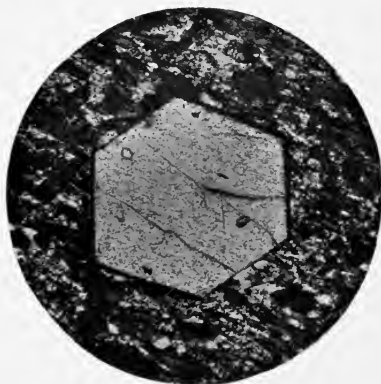


FIG. 45.—GARNET, in biotite schist. N.W. Rhodesia.

Usually colourless or faintly pink; sometimes deeply coloured and nearly opaque. Frequently found in good crystals, also granular. Sections are usually hexagonal, octagonal, or rounded. There is no well-developed cleavage, and irregular cracks are frequent.

The refractive index is very high (1.8). Isotropic as a rule, but grossular and melanite occasionally show ano-

malous double refraction, when a zonal structure sometimes becomes evident.

The chief varieties are :—Grossular (lime garnet), sometimes faintly pink or green, but usually colourless in sections ; Almandine (common garnet), pink in sections ; Melanite (lime-iron garnet), brown in sections ; Spessartine (Manganese garnet), red, orange, or colourless ; Pyrope (magnesian garnet), bright red, but never well crystallized, and colourless in sections.

Rare as a constituent of igneous rocks, but common as a contact mineral, and also in some apparently dynamo-metamorphic rocks.

Analyses of Garnets.

	<i>Grossular</i> from Crystalline Limestone, Xalastoc, Mexico. (Seebach.)	<i>Alman- dine</i> from Andesite, Ana- mushi, Japan. (Shimizu.)	<i>Andra- dite</i> from Nepheline "Syenite," Bancroft, Canada. (Harrington.)	<i>Melanite</i> Frascati, Italy. (Seebach.)	<i>Spessar- tine</i> Loch Maree, Scotland. (Wilson.)	<i>Pyrope</i> Colossus Diamond Mine, Rhodesia. (Mennell.)
SiO ₂	40.79	36.74	36.604	34.74	37.45	40.43
TiO ₂	—	—	1.078	1.54	.25	—
Al ₂ O ₃	21.70	20.71	9.771	5.44	20.08	19.13
Fe ₂ O ₃	.18	—	15.996	21.95	4.35	4.94
Ca ₂ O ₃	—	—	—	—	.34	2.12
FeO	.43	34.91	3.852	1.99	15.05	8.66
MnO	1.07	1.67	1.301	.65	19.61	.12
CaO	35.63	2.11	29.306	32.58	1.86	4.44
MgO	.39	3.27	—	1.48	.30	20.33
K ₂ O	—	—	—	—	.57	—
Na ₂ O	—	—	—	—	.26	—
Loss	—	—	.285	—	.22	—
	100.19	99.41	99.577	100.37	100.32	100.17
Sp.Gr. =	3.506		3.739	3.774	4.1	3.72

Wollastonite, CaSiO₃. Monoclinic. H = 5 ; G = 2.8. Gelatinizes with hot hydrochloric acid.

Transparent and colourless in thin sections. Forms tabular crystals elongated in the direction of the ortho-axis. Also occurs in fibrous aggregates. Longitudinal sections are lath-shaped and give straight extinction ; cross sections are six or eight-sided. The cleavages are

parallel to the base and the orthopinacoid, intersecting at an angle of $90^{\circ} 30'$. In cross sections, extinction takes place at an angle of 32° to the base. Sometimes twinned on the orthopinacoid.

R.I. fairly high (1.63). D.R. low, the maximum interference tint in ordinary sections being orange of the first order.

Wollastonite is a contact mineral chiefly occurring in marbles, etc., originally siliceous, or in which the metamorphism has been accompanied by injection with silica.

Idocrase or *Vesuvianite* (lime alumina iron silicate). Tetragonal. $H = 6\frac{1}{2}$: $G = 3.4$. Not attacked by acids.



FIG. 46.—ZEOLITES. (Analcime & Natrolite.) In Dolerite of Salisbury Crags, Edinburgh, Scotland.
× 20 diam.

Yellowish-brown, or greenish in colour. Seldom well crystallized, and then it is prismatic. Cleavage very imperfect prismatic. Irregular cracks are common.

Refractive index very high (1.72). Double refraction very weak. Absorption strong. In longitudinal sections there is straight extinction.

It occurs in a few contact rocks, especially crystalline limestones.

*Zeolites.**—These minerals are all hydrous silicates of alumina *plus* other bases, except pectolite, which is non-aluminous. In hand specimens they are white, grey, yellowish, greenish or pinkish, but all of them are colourless in slices when undecomposed. The following are the principal zeolites, grouped according to the bases they contain, apart from alumina:—*Soda*: analcime and natrolite. *Soda and lime*: mesolite and pectolite. *Lime*: chabazite, heulandite, laumontite, prehnite, scolecite, and stilbite. *Potash and lime*: apophyllite. *Baryta*: harmotome and brewsterite.

Three of the above never occur in elongated crystals or fibres, namely, analcime, apophyllite, and chabazite. All three are feebly birefringent, the first mentioned being often isotropic. Of those which assume elongated forms, prehnite and pectolite are at once distinguished by having refractive indices as high as calcite, and double refraction as strong as olivine. All the rest have a refractive index near that of quartz. Natrolite, laumontite, mesolite, scolecite and brewsterite have double refraction about the same as quartz. The two first are positive and the rest negative, while natrolite alone gives straight extinction. Stilbite, heulandite and harmotome have very weak double refraction. A few blowpipe tests in conjunction with the above optical data will enable most zeolites to be referred to their proper species.

All the group occur almost exclusively as infillings of the amygdaloidal cavities of the volcanic rocks, especially the more basic types.

* See especially Lévy and Lacroix, *Les Minéraux des Roches*, pp. 296-320.

CHAPTER VIII.

The Igneous Rocks: their Classification, Structure, &c.

It is generally admitted that the primitive crust of the earth was of igneous origin, that is to say, that it resulted from the consolidation of matter originally in a state of fusion. This crust must have been made up of petrological units very different in many respects from the igneous rocks with which we are at present acquainted. Nevertheless, it is important as the first source from which sedimentary accumulations could be built up, and the igneous masses of later date have continued to provide material for those of the stratified series, with increasingly important contributions from the older strata themselves. Both igneous and sedimentary rocks have also yielded, from time to time, to the powerful influences of heat and pressure, acting either singly or in concert, so that we have to consider, besides the above-mentioned groups, another of metamorphic character. We see, moreover, that the igneous rocks are of importance to the petrographer, not only on account of their great abundance, but from their position as the ultimate source of the materials out of which the other classes have been formed. They will accordingly receive a large share of our attention in the following pages.

The igneous rocks are themselves aggregates of various minerals, chiefly *silicates* (of alumina, iron, lime, magnesia, and the alkalis), together with uncombined *oxides* of silicon and iron, as well as small quantities of other substances, such as compounds of titanium, zirconium, phosphorus, chlorine, fluorine, boron, and sulphur. A few, indeed, which have consolidated from fusion with great rapidity, are partly or entirely glassy; but these are of extremely limited distribution compared with the crystalline types. The classification of the igneous rocks which is here followed is a strictly chemical one, and therefore only indirectly related to their mineralogical

composition ; but, for descriptive purposes, a knowledge of mineralogy, and particularly of the features presented by minerals in thin slices, as seen under the microscope, is of the first importance, and has accordingly been dealt with in considerable detail.

Modern petrography may be said to date from the time when the microscope came into general use for the examination of rocks. It appears to have been first employed for the purpose by Jacopo Beccari who, on March 3rd, 1711, presented to the Bologna Academy a paper entitled "De Variis Arenis," in which were embodied the results of microscopical work. Cordier, also, in 1807 and succeeding years, published some interesting researches into the composition of rocks, carried out by examining their powder under the microscope, and with the blowpipe.* His investigations were not, however, followed up, and it was only in 1849 that Dr. Sorby, by preparing thin sections, first demonstrated the real importance of the microscope in geology.† Since that time the preparation of sections has reached a state of great perfection, and the advances made in our knowledge of rocks as a consequence of the application of the microscope to their study have been truly astonishing. In the development of the methods introduced by Sorby, Zirkel took an especially prominent part, and other German investigators have done much to advance petrological research. But, as Lapparent has justly remarked, the general tendency of petrographers has been to make "of lithology a science apart, much more closely connected with mineralogy than with geology." The great disparity between the growth of our general theory and that of our knowledge of the composition and structure of the rocks themselves must be attributed in large measure to this fact. Petrography, indeed, is in imminent danger of becoming an end in itself rather than a means of advancing geological science as a whole. It must, therefore, on no account be forgotten that field and microscopic observations should go hand in hand, and many a mistake will be avoided through keeping this fact in

* These afford a most interesting example of how much can be accomplished by very simple means. See Cole, *Aids in Practical Geology*, pp. 110-113 ; also Crook, *Geol. Mag.*, 1907, pp. 157-165.

† See Judd, *Geol. Mag.*, 1908, pp. 193-204.

mind. The greatest care is necessary in drawing conclusions from microscopic study alone with regard to rocks of doubtful origin. And it is not enough to recognise the interdependence of the different modes of geological investigation. For we find, as Harker has pointed out,* that the igneous rocks, which have been allowed to become the special province of the petrographer, are in no wise to be regarded as mere meaningless interpolations in the stratigraphical sequence; they are closely bound up with the geological history of the districts in which they occur, and their minute study often proves of the greatest assistance in unravelling the nature of the processes by which such areas have assumed their present structural and physical features.

IGNEOUS ROCKS.—In spite of the large share of attention the igneous rocks have received from petrographers, the systematisation of the knowledge obtained by their study has not advanced much. As a consequence of this and of a hankering after a so-called “natural system” of classification—undeterred by the fate of that of Mohs, applied to such much better defined bodies as minerals—very few authors agree even as to the basis on which a division should be founded. The most widely used classifications are based to a large extent on the nature of the minerals present, but even these systems show the influence of chemical and structural considerations which they professedly exclude. They all, moreover, have a tendency to emphasise unimportant variations, especially those due to differences in the ferro-magnesian constituents and the presence or absence of such a relatively rare group as the so-called “felspathoids.” What are usually termed genetic systems of classification are obviously foredoomed to failure, if only for the reason that a single mass of rock may show the most extreme variations of composition. What is wanted is not a name to cover all the types evolved, or rather presumed to have been evolved, from a single magma, but a series of names serving to define the variations themselves with the greatest convenience.

COMPOSITION. The best way to grapple with such a

* *Science Progress*, vol. ii, 1894, p. 18.

state of affairs appears to be by the adoption of the simplest method which fairly expresses the relation of the types. Chemical composition seems the surest basis on which to build, as it does at least enable us to arrive at an accurate correlation of the products of crystallisation under the most diverse circumstances. It is practically impossible to take into account the varying proportions of *all* the constituents of a magma, and some anomalies are sure to occur. As, however, all the most important rock-formers are silicates, by grouping the rocks according to the amount of silica they contain, we arrive at a fairly reliable standard of comparison, especially as the proportions of the other constituents vary with considerable constancy as, or inversely as, the silica percentage. We may accordingly adopt chemical composition as indicated by the silica percentage as a feature of primary importance in expressing the relationships of the various types.

OCCURRENCE. The field geologist is, moreover, able to divide the masses of igneous rocks he encounters in the field into three classes: (1) the lava flows which have been poured out at the surface of the earth, and have accordingly cooled down under the pressure of the atmosphere only; (2) the dykes which represent the filling of fissures, up which molten material has forced its way, and through which lavas in many cases rose to the surface; (3) the plutonic masses representing the residuum of those great reservoirs of molten rock which appear to underlie regions where volcanic activity is rife. They have probably arisen from the melting of all classes of material through depression to a depth at which the temperature was sufficient to cause fusion on subsequent relief of pressure. Such masses have cooled at great depths below the surface and therefore under pressures which must be expressed in tons to the square inch, though they may often, like the dyke-rocks, have made their way upwards before consolidation to considerable distances above the positions at which they had their origin as fluid magmas. All these differences of occurrence show themselves in the structure of the rock just as the variations in chemical composition are manifested in the minerals which are present. Some authors only recognise two main divisions (plutonic or abyssal, and volcanic or superficial) grouping some of the dyke rocks

with the lavas, and some with the deep-seated types. But by adopting a three-fold division we not only keep in view the fact that petrology is, after all, a branch of geology, but we render our classification more logical. The dyke rocks (hypabyssal group of Brögger), indeed, include types which have consolidated under very varying conditions. The recognition of such a division, however, certainly brings us nearer to a natural classification, as we are thus enabled to confine the terms plutonic and volcanic to rocks which have crystallised respectively under precisely similar circumstances. It is important to remember that a lava flow is, from a geological point of view, fundamentally distinct from a dyke, no matter how similar the two may be in composition and mineral constituents. Further, although a lava is simply the overflow from a filled-up fissure (*i.e.*, dyke), there is no difficulty in seeing that the point where dyke merges into lava is the last thing that is likely to be preserved, being, in the vast majority of cases, high up on a steep mountain side and exposed to constant vicissitudes in the shape of explosions as well as being peculiarly accessible to the ordinary agencies of denudation. A plutonic mass is also to be considered as something altogether different from a dyke, though much confusion has been caused by the practice of calling coarse-grained dykes plutonic rocks. Though often termed intrusive, especially in the sense of having actually solidified in contact with the surrounding and overlying rocks, they are not so in the sense that a dyke is, and it is unfortunate that no term exists to better define their relationship to the adjacent rocks. A plutonic mass almost invariably occupies the axis of a denuded anticline* and no doubt the formation of the anticline was the cause of the relief of pressure which gave rise to the fusion of the subjacent rock. The latter was in no way the cause of the movement, the essential feature of the whole process being that the magma simply rose with the overlying beds, afterwards solidifying as a huge dome or "bathylith," extending downward to an unfathomable

* It is this fact which has no doubt given rise to the widespread application of the "laccolite" idea, which seems of very doubtful validity wherever it implies the presence of unabsorbed sediments below a truly *plutonic* mass.

depth. The presence of the dykes that so frequently occur as offshoots from the mass is entirely in conformity with such a view, as the relief of pressure would be merely relative and not absolute. There would, in fact, still be enormous pressure acting on the fused mass. In accordance with the laws of hydrostatics, the weight above would cause the molten rock to exert equal pressure on all parts of its solid covering, and the lines of least resistance, whether to the corrosive power of the fused material, or to its disruptive force, would speedily be sought out.

NOMENCLATURE. The question of nomenclature is as serious as that of classification, and while authorities differ as to the application of even the best-known terms, meaningless and barbarous-sounding appellations are every day being introduced for unimportant varieties, a practice which is a source of bewilderment to the student and of annoyance to the systematic petrologist. The presence or absence of particular minerals, though of great importance from a descriptive point of view, and as an indication of the composition of a rock, is certainly not sufficient to justify expression by distinct names. In this work one name only will be used for each division recognised, as shown in the following table :

	Plutonic (= large masses)	Intrusive (= dyke rocks).	Effusive (= lava flows).
Acid, over 65% silica	Granite	Granophyre	Rhyolite
Sub-acid, 60 to 65%	Syenite	Orthophyre	Trachyte
Sub-basic, 55 to 60%	Diorite	Porphyrite	Andesite
Basic, 45 to 55%	Gabbro	Dolerite	Basalt
Ultrabasic, less, than 45%	—	Picrite	Limburgite

Little is required by way of comment on this system of classification. Most of the above terms are in constant use with very much the significance given to them above. It will be observed, however, that the term "granophyre" is applied to *all* the acid intrusives. It may perhaps be objected to the grouping here adopted that it is not sufficiently elaborated for the purposes of modern descriptive petrography. At the present stage of progress, however, over-elaboration is a much more serious stumbling-block than simplicity, and it is easy, in conjunction

with the above scheme, to express varietal differences by prefixes ; such a course having the immense advantage of being readily comprehensible, even if occasionally somewhat cumbrous. Thus "glassy dolerite" is much to be preferred to the very ambiguous "tachylite" and "nepheline dolerite" to any of the multitudinous terms which have been invented to express the same thing. It is necessary, sometimes, to speak of a "hornblende-augite-porphyrite," but it is quite possible to avoid such length in some cases. Thus, instead of "augite-enstatite-andesite," "pyroxene-andesite" is a useful term, provided it is systematically used to signify a rock in which both monoclinic and rhombic varieties are present. In many cases a prefix can be dispensed with ; thus diorites are so constantly composed of hornblende and plagioclase, and dolerites of augite and plagioclase, that these terms need only be qualified when some other important constituent (*e.g.*, enstatite) makes its appearance.

QUANTITATIVE CLASSIFICATION. An able and interesting attempt has been made by several leading American petrologists to classify the rocks on a chemical and quantitative basis. Starting from the chemical analysis, the magmas are divided into two groups, *salic* and *femic*, the rock-forming minerals being similarly divided, with a subordinate *alferric* group. *Salic*, it may be explained, indicates the compounds rich in silica and alumina, while *femic* means ferro-magnesian, and *alferric*, alumina-iron compounds. The rocks are classified according to the relative proportions of their *salic* and *femic* minerals ; not, however, the minerals actually present as seen in a microscopic section, but certain hypothetical standard or *normative* minerals calculated from the chemical composition of the rock as a whole. Among the conventions adopted is, for example, to regard muscovite as a mixture of corundum and orthoclase, while the "alferric" minerals like biotite are similarly treated. Consequently the actual constitution or *mode* of the rock may and often does differ extremely from its *norm* or calculated composition. The latter, however, is suggested by the authors to represent compounds possibly present in the molten magma. On this basis, the principal classes are five in number, defined as follows :

(1) *Persalane* : extremely salic ; ratio of salic minerals to femic greater than 7:1.

(2) *Dosalane* : dominantly salic ; ratio of salic to femic between 7:1 and 5:3.

(3) *Salfemane* : equally salic and femic ; ratio between 5:3 and 3:5.

(4) *Dofemane* : dominantly femic ; ratio between 3:5 and 1:7.

(5) *Perfemane* : extremely femic ; ratio less than 1:7.

The division of classes into sub-classes is based on the proportion of the standard or normative minerals to one another, a matter which need not be entered upon here, as it scarcely seems likely that such an artificial system will ever become anything like universal. An obvious criticism is that a complete chemical analysis cannot be made of every rock that it is desired to name ; indeed the authors of the system recognise the need of terms for field use. The admirable exposition of the method and the complete manner in which the scheme has been elaborated have, however, been of much service in drawing attention to the recently somewhat neglected chemical relationships which, after all, are of primary importance in the study of rocks.*

STRUCTURE. The structure and texture of the igneous rocks vary greatly, but a close relationship can be established between these features and the conditions under which consolidation has taken place in each instance. A few rocks are wholly *vitreous*, or glassy and slag-like, but the vast majority are entirely or partly crystalline. Those rocks which are of plutonic origin, such as the great granite masses that are to be met with in all parts of the world, are invariably *holocrystalline*, that is to say, entirely composed of crystals. This is not to be interpreted as implying that their individual grains show well-developed external form, but that they possess all those properties of which crystalline form is the outward indication. As a matter of fact, the crystals of these rocks rarely show good faces ; they are usually nearly all *allotriomorphic*, as distinguished from crystals with well-developed outlines, which are said to be *idiomorphic*.

* See also Warth, *Geol. Mag.* 1900, p. 273.

This arises from the fact that the magma has crystallised as a whole, and not in absolutely definite stages, though a certain order is nevertheless evident in the sequence of crystallisation of the various constituents. The plutonic rocks are further distinguished, from the same cause, by their evenness of grain, the crystals being comparatively uniform in size. What may be termed a *pseudo-porphyritic* texture is sometimes observed; this arises, as a

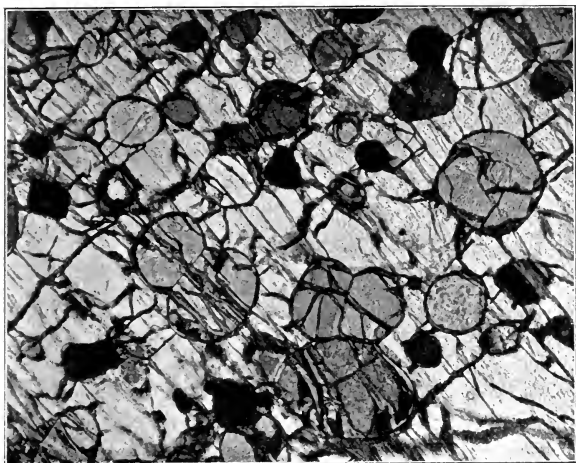


FIG. 47.—POECILITIC STRUCTURE. (Olivine in Enstatite.) In Picrite of Belingwe, Rhodesia. + nicols. $\times 70$ diam.

rule, from the occurrence of large-sized grains of the chief constituent of the rock, and must be carefully distinguished from the true porphyritic structure (see after). This merges into the interesting structure called *poecilitic*, which arises when a mineral forms large crystals, studded with enclosures of others which have crystallised in the normal course before it, but have not attained any great size. As the even-grained *granitic* texture is characteristic of all the large rock masses which are obviously plutonic

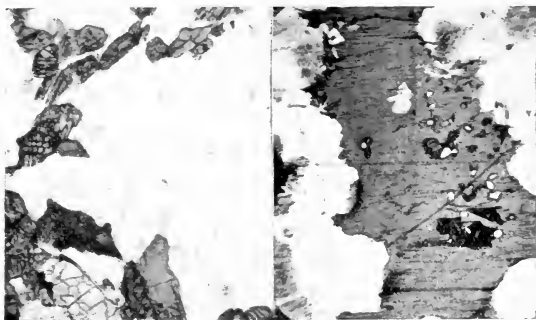
in origin, we may take this as the distinguishing feature of the whole class, and rigidly exclude from it those minor intrusions which show marked departures from the granitic standard.

ORDER OF CRYSTALLISATION. Many of the crystalline schists have a structure so closely allied to that of the normal plutonic rocks that it is necessary to carefully distinguish them, and it is evident, indeed, that a number of so-called "diorites," etc., really owe their immediate characters to metamorphic action. We have already remarked that the plutonic rocks have as their distinctive feature crystallisation *en masse*, but a rock which exhibits simultaneous crystallisation in too great perfection must be looked upon with considerable suspicion. For it will be found, on careful examination, that though they have mutually interfered with one another to a large extent, the different minerals of a plutonic rock nevertheless show a well-marked tendency towards a definite order of crystallisation. Thus, if one mineral is partly enclosed in another, the former has obviously crystallised first, and a little consideration will show that the same argument may be applied to a mineral which presents crystal faces to another, or even shows a convex outline towards it, in default of perfectly developed form. From the study of such points Rosenbusch has been able to deduce a general order of crystallisation which holds good with few exceptions. At first sight it would seem that the most infusible minerals ought to separate out before the others, and that this is really the case has been argued by Messrs. Fouqué and Lévy. Their explanations of the observed anomalies are, however, unconvincing, and it must be remembered that the molten magma is to be regarded from the same point of view as a solution. Those substances which most readily saturate the solvent will accordingly separate out first, and it has been found that the order of crystallisation is in the main an order of decreasing basicity, the most basic compounds being the first to crystallise.* A rough summary of the order may be made as follows :

* Compare the melting points : Magnetite, 1200°; Olivine, about 1600°; Enstatite, 1500°; Augite, 1375°; Hornblende, 1100° (?); Leucite, over 1500°; Nepheline, 1200°; Anorthite, 1550°; Albite, 1250°; Orthoclase, 1300°; Quartz, 1600°.

- (1) *Accessories* : apatite, zircon, sphene, magnetite, etc.
- (2) *Ferro-magnesian minerals* : olivine, pyroxenes, hornblende, micas.
- (3) *Felspars and feldspathoids* : leucite, nepheline ; anorthite to albite ; orthoclase and microcline.
- (4) *Quartz*.

The normal order of crystallisation, so far as it can be traced, is strictly adhered to in the plutonic rocks except



(1)

(2)

FIG. 48.—(1) Large irregular plate of felspar, with previously consolidated Augite, Apatite, and Sphene pushed out to its edges. In Augite-Diorite of Hillside, nr. Bulawayo. Rhodesia.

(2) Plate of biotite with numerous enclosures of Apatite, Magnetite, and Zircon. In granite, north of the Zimbabwe Ruins, Rhodesia.

in the rarest cases, when microcline may be preceded by the quartz, and patches of micropegmatite may occur. In the schists there is no such definite order. A mineral may contain enclosures of another in one instance and the reverse may be the case with adjacent crystals. Crystal-line form is, moreover, wholly wanting as a rule, and even where there are indications of it, the crystals usually enclose granules of minerals towards which they elsewhere present crystal faces. Thus garnet frequently encloses quartz, mica, etc., even when it occurs in well-developed crystals, and those minerals only form irregular granules. This is due to the simultaneous crystallisation of the

various minerals, combined with the want of fluidity, preventing the migration of their molecules to more than a very limited extent. It may be noted here that in some cases the order of crystallisation is by no means obvious at first sight. Some minerals, such as the feldspars, have a strong tendency to push away to their margins the previously formed accessories, etc. On the other hand, minerals like biotite seem to crystallise by preference on nuclei of pre-existing minerals. (Fig. 48.)

PRINCIPLES OF SEPARATION. Recently much attention has been directed to the chemical and physical principles on which the separation of crystals from a molten magma necessarily depend. It cannot be said, however, that any great advance has yet been made in the application of the theory to the observed facts. Among others, the conception of rock magmas as wholly or partly made up of eutectics or mixtures of eutectics has been much debated. It has long been known that certain mixtures of fused salts tend upon cooling to deposit crystals of whichever is in excess of a certain fixed proportion until that proportion is left in the residue, which thereupon solidifies *en masse*. Guthrie, by whom the name eutectic was given to mixtures in the proportions required for such simultaneous crystallisation, suggested the applicability of his observations to rock magmas. Teall elaborated this conception, and suggested that micropegmatite might be the quartz-feldspar eutectic. The great difficulty in the way of applying such principles is the fact that rock magmas are of very complex constitution. Furthermore, the co-existence in certain rocks of antithetical minerals like magnetite and quartz strongly suggests ionisation, or may imply that the various oxides exist uncombined and not as silicates. It is also very rare for the dominant constituent to separate out first. Observation, indeed, as indicated by Rosenbusch's empirical law, appears to lead to a diametrically opposite conclusion. It seems rather as if the order of separation was based on what, for want of a better description, might be termed *decreasing specialisation*. Thus, although the more usual accessories seldom make up more than one per cent. of a rock, they invariably separate out first. It is significant, moreover, that they are largely non-silicates, *e.g.*, apatite,

magnetite, ilmenite, chromite, spinel, rutile, etc., or else compounds of the rare elements, *e.g.*, zircon, orthite, sphene, etc. The ferro-magnesian minerals are also more "specialised" than the other constituents, of a granite for example, iron and magnesia occurring in very small amounts compared with alumina, silica, and the alkalis. Yet biotite and hornblende invariably separate out first, and seem always to include in their composition the rarer elements present, apart from those in the accessories.

INTERGROWTHS. Interesting structures arise from the intergrowth of two minerals in definite crystallographic relationship, one being enclosed within the other, while

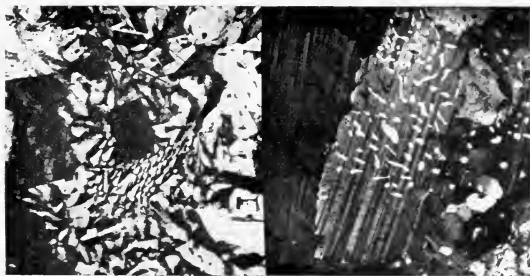


FIG. 49.—(a) ORDINARY MICROPEGMATITE, in Porphyrite of Wood's Point, Victoria, Australia. (b) VERMICULAR MICROPEGMATITE, in Granite of Jahonda, Rhodesia. + nicols. $\times 50$ diam.

their vertical axes are continuous or parallel, for example, as with epidote and orthite, or augite and hornblende. Cases also occur where one mineral encloses numerous granules of the other, all the enclosures preserving the same orientation over considerable areas, and usually forming skeleton crystals. Such a relation is common between felspar and quartz, and the structure is termed *graphic*, or on a minute scale, *micrographic*, while the intergrown minerals are often collectively referred to as micropegmatite. Some intrusive rocks show intergrowths of this kind in the greatest perfection. Other minerals occur in micrographic intergrowth, in the same way as quartz and

felspar. Among them may be noted augite and enstatite, augite and felspar, augite and nepheline, augite and ilmenite, enstatite and nepheline, felspar and nepheline, olivine and felspar, quartz and tourmaline, etc.

DEPARTURES FROM THE PLUTONIC ORDER. There are many intrusive rocks in which departures from the normal order of crystallisation afford the principal distinction from the truly plutonic types. Thus in the holo-crystalline dolerites, augite is frequently preceded by the felspars. It does not seem to be sufficiently realised

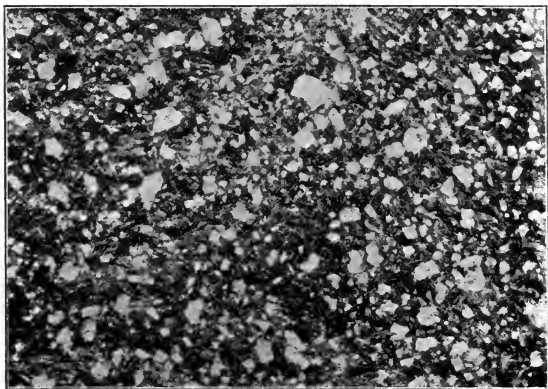


FIG. 50.—PORPHYRITIC STRUCTURE. (Megascopic.)

that this is a natural consequence of differences in the conditions of consolidation, such as variations of temperature and pressure. There is nothing capricious or extraordinary about it when one considers what the physical effects of such circumstances must be.

STAGES OF CONSOLIDATION. In the intrusive rocks and the lavas it is indeed obvious that the crystallisation has often taken place in two or even more distinct stages. Thus material forced towards the surface from a magma in which crystallisation was proceeding, would carry with it a crop of crystals, while the still molten

portion might consolidate eventually as glass, or, under favourable conditions, give rise to a second *generation* of crystals, which would envelope the first. Similar features may follow upon mere decrease of temperature, as Messrs. Fouqué and Lévy showed in their well-known synthetic experiments. In either case the resulting structure is termed *porphyritic*, and the crystals of prior consolidation are known as *phenocrysts*, the later products being called the *groundmass*. In many instances it happens that as a mass of molten material is forced upwards, the pressure is reduced at a greater rate than can be compensated for by cooling. Now reduction of pressure produces the same effects as increase of temperature, and under

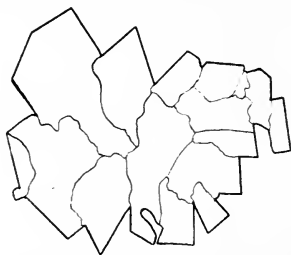


FIG. 51.—GLOMERO-PORPHYRITIC FELSPARS, in the Victoria Falls, Falls Basalt. $\times 60$ diameters. Boundaries of grains indicated as seen with + nicols.

such circumstances the phenocrysts already developed tend to melt and redissolve in the magma. Evidences of such *corrosion* or even complete *resorption* of the first generation of crystals are, in fact, frequently observed in rocks that have finally consolidated at or near the surface. It does not do, perhaps, to lay very much stress on crystallisation before extrusion, the intratelluric origin of phenocrysts being by no means clear in most cases. It may be remarked that there are some rocks of a porphyritic character in which the usual individual phenocrysts are represented by aggregates of crystals of one or more minerals. All such types may be grouped with those which have been termed *glomero-porphyritic* by Judd. The glomero-porphyritic aggregates, or *composite phenocrysts*,

as they may more conveniently be termed, show very interesting variations in the relations of their constituents. Some are grouped in a manner recalling the granitoid texture of the plutonic rocks, not showing well-developed faces to one another, though they may do so to the groundmass of the rock. Excellent examples are afforded by the Victoria Falls basalts (felspars, sometimes with augite). Iddings describes the occurrence of micropegmatite patches as the equivalent of porphyritic crystals in rhyolites from the Yellowstone Park and from Nevada. They are also recorded by Kynaston from the Cheviots and by Harker from Pembrokeshire, and the latter author mentions the occurrence of ovoid patches of quartz and

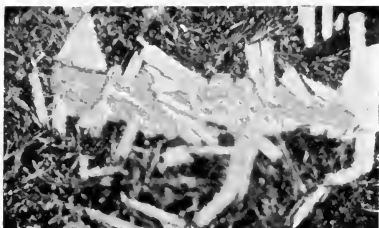


FIG. 52.—GLOMERO-PORPHYRITIC AGGREGATE OF AUGITE FELSPAR, with ophitic structure, Dolerite of Tati, Bechuanaland. $\times 50$ diam.

felspar related in poecilitic fashion. A dolerite from the Monarch Mine, Tati, Bechuanaland, shows irregular patches of augite and felspar with an ophitic relation, taking the part of phenocrysts in a very fine-grained groundmass containing much glass. More or less related to composite phenocrysts appear to be the spheroidal, nodular, or orbicular structures seen in certain granites, etc. They seem due to a clotting together of the first products of crystallisation, to imperfect absorption of foreign materials, or to a deposition of crystals induced by inoculation with extraneous substances.

VARIOUS STRUCTURES. A porphyritic structure is particularly characteristic of the dyke rocks, though it is

also common among lavas. Among the basic rocks, however, we have the peculiar structure known as *ophitic*, due to the lath-shaped feldspars being embedded, not in a fine-grained groundmass, but in large plates of augite of later consolidation. Owing to the readiness with which basic material appears to crystallise, this feature constitutes the main distinction in the coarse-grained varieties between the truly plutonic and the ordinary intrusive types. The true gabbros exhibit the normal order of crystallisation, while in the dolerites it is frequently

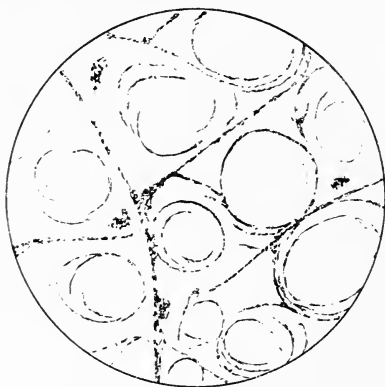


FIG. 53.—PERLITIC CRACKS IN RHYOLITE, Meissen, Saxony. $\times 20$ diam.

reversed as regards the feldspars and the ferro-magnesian minerals.

Those rocks, which are largely *glassy*, belong chiefly to the group of lavas, though many examples are to be found among the marginal modifications of quickly cooled dykes. They possess certain interesting peculiarities of structure. Contraction during cooling has often produced cracks, some of which may be straight and nearly parallel. In other cases they are roughly circular, or by interference amongst those tending to assume a circular shape, divide up the rock into polygonal areas. In these cases the

structure is termed *perlitic*. It presents distinct analogies to the columnar aspect of many basalts, and is even more closely related to the spheroidal structure brought out in many rocks by weathering. Many glassy rocks and ground masses show a tendency towards crystallisation in the development of cloudy or fibrous patches, the fibres of which often radiate from a common centre, or from the corner of an embedded crystal. When this tendency is pronounced we have the *spherulitic* structure. In many

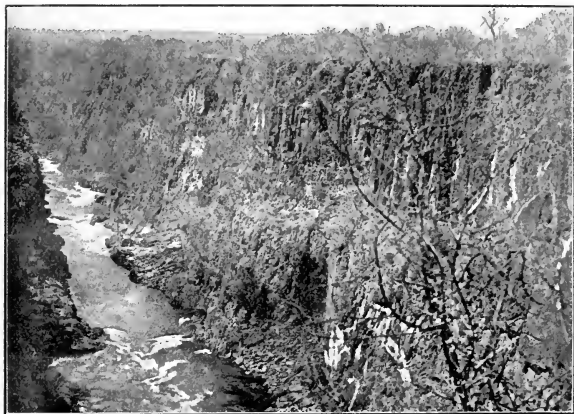


FIG. 54.—GORGE OF THE ZAMBESI RIVER, below the Victoria Falls, showing columnar structure of the basalt flows. Section about 500 feet high.

cases it is only revealed in polarised light, and it may then be regarded as usually of secondary origin. That is to say, it is due to causes such as heat, pressure and aqueous action effecting molecular rearrangement in material which actually consolidated as glass. Such a process is known as devitrification. It need not express itself in a spherulitic structure, but may merely be revealed by an apparently homogeneous groundmass splitting up between crossed nicols into an indefinite aggregate of extremely minute flecks and fibres acting on polarised light. A

similar imperfectly vitreous groundmass when original is frequently termed *stony* or *lithoidal*. A well-marked *flow-structure* is shown by many lavas, particularly the more acid types. It may take the form of an alternation of light and dark bands, especially in imperfectly crystalline rocks, or be indicated by the "streaming of the feldspars." It may sometimes be seen on the polished surface of a rock in which it is by no means obvious under the microscope (*e.g.*, the Victoria Falls basalt). Intrusive

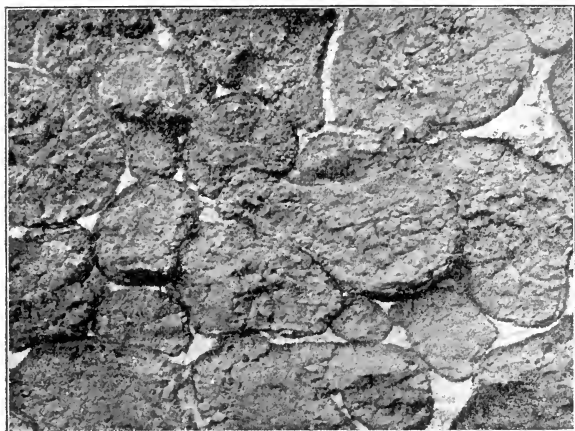


FIG. 55.—PILLOW LAVA (Olivine Basalt), Cape Wanbrow, New Zealand.
(After Park.)

rocks may also show well-developed flow-structures, in fact the gneissic aspect of many granites has clearly been impressed upon them before their complete consolidation.

The most distinctive feature of lava flows is undoubtedly the *vesicular* nature of their upper and under surfaces, due to the escape or expansion of imprisoned steam. In the case of the upper portions, denudation may have removed all traces of it before the rock has been covered over with sediment, but it may be said with considerable confidence

that every true lava will be found more or less vesicular in its lower parts. When, as is usually the case, except with recent rocks, the vesicles have been filled up by the infiltration of such substances as chalcedony, calcite, or members of the zeolite group, the rock is called *amygdaloidal*. A few dykes exhibit an amygdaloidal structure, but the amygdules are usually small, spherical, and sparsely distributed, and any highly vesicular rock may be regarded with some certainty as a lava. The curious *pillow structure* shown by certain basic rocks is confined to lavas. Dr. Tempest Anderson actually witnessed the formation of the "pillows" in the Sandwich Islands, while they also occur in the Tertiary basalts of New Zealand, as well as in the Carboniferous lavas of Somerset and the Devonian ones of Devonshire. What appear to be relics of the same structure in Archæan rocks are to be seen among the "epidiorites" in several road cuttings at Bulawayo.

DESCRIPTIVE TERMS. Attention may be drawn, in conclusion, to certain terms used in describing rocks. Thus its constituents are said to be *original* or *secondary*, according as they are considered to have formed at the same time as the rock acquired its distinguishing characteristics, or to be due to some subsequent process of alteration. A rock may also contain *xenoliths*, or derived constituents, picked up in its passage through other rocks. Then again, the original constituents of a rock may be divided into two categories: essential and accessory. The term *essential* is applied to those minerals which make up the bulk of a rock and give it its distinctive nature, while the term *accessory* is best reserved for those minerals which never form a large proportion of any rock mass, but are nevertheless constantly present; others, of greater general importance, only occurring in small quantities in the type under consideration being called *subordinate*. The principal mineral, and particularly the most abundant variety of felspar, is often termed *dominant*. Thus one might speak of the dominant orthoclase, the essential hornblende, the subordinate quartz, and the accessory sphene, in a syenite.

CHAPTER IX.

Origin and Variations of the Igneous Rocks.

BEFORE proceeding to go into details regarding the structure and mineral composition of the different classes of igneous rocks, it will be well to give some attention to the question of the relationships of the various types.* Some indication has been given in the preceding pages of the views that are held concerning the origin of these rocks, and the influence of such views on classification has been important. Many authorities hold that all types have their source in a common magma, and the name "petrographical province" or "comagmatic region" has been applied to areas where similar peculiarities of constitution are found to prevail among rocks whose actual composition is very varied. Thus some areas tend to show high alkali percentages in all classes from basic to acid, while others have varieties consistently low in potash or soda. The evidence has even been held to point to some principle of distribution both in time and space of the chief types of igneous rock. As in so many generalisations, the tendency has been shewn by closer investigation to have been over-emphasized, and our detailed knowledge of most regions is not sufficient for much confidence to be placed in theoretical deductions from the characteristics at present known. How much remains to be learnt in even the best known areas is well illustrated by the recent discoveries of highly alkaline rocks† at many points in Scotland, and they have also been located in the typically non-alkaline volcanic districts of Australia and New Zealand.

DIFFERENTIATION. The idea of some sort of genetic relationship or community of origin has, however,

* For an interesting discussion from a different standpoint see Teall, Presidential address to the Geological Society, *Q.J.G.S.*, vol. 57, 1910.

† For a useful summary of information regarding one group of these see Tyrrell, *Geol. Mag.*, 1912, pp. 69-80 and 121-131.

attained a large measure of popularity, though at the same time no particular theory has met with general acceptance. What have been termed "differentiation" processes have been most favoured, such differentiation being ascribed either to some process of segregation, or else to such methods as fractional or progressive crystallisation, complicated it may be, by straining, liquation, convection currents, eruptions, or partial consolidation. The segregation hypothesis is possibly a *vera causa* to some extent, especially in the case of comparatively small masses of rock. It postulates the existence of a homogeneous magma, wherein takes place the drawing together of acid or basic materials, respectively, from the general mass, or a concentration of basic material resulting in the leaving behind of an acid residuum, each portion eventually consolidating, perhaps, as an independent rock mass. The concentration of magnesia and nickel in the most basic rocks may be a true segregation effect in the first stages of the process, and so, too, are certain cases of the separation out of magnetite or ilmenite from a gabbro, or dolerite, and of chromite from a picrite. But these rocks are of very limited occurrence, and cover very small areas as a rule. Moreover, such separations as we have referred to seem dependent on diffusion, and, except in the case of small rock masses, complete separation would be impossible, since the fastest conceivable diffusion is incapable of producing such effects on a really large scale within any reasonable period of geological time. In any case, such a result would only be possible during the absolute quiescence of the magma. It may be noted that the mere existence of immense undifferentiated plutonic masses like the Canadian, West Australian and Rhodesian granites is in itself an extremely strong argument against the validity of explaining rock variation by segregation processes. Those granites have consolidated under such conditions as regards cooling, quiescence, etc., as should have been eminently favourable to segregation, and their comparative uniformity is very difficult to explain away on the assumption that it is of any real importance.

REFUSION. If now we leave differentiation hypotheses altogether out of account and turn to the wider question of the origin of igneous magmas, we are led to

view the whole problem from quite a different standpoint, and we may even go to the extreme of refusing to grant the necessity of accounting for rock variation otherwise than as a natural consequence of primary magmatic differences of a local character. Actual observation in areas where the igneous rocks are particularly well developed leads us, in fact, to the conclusion that no large rock mass ever existed in a strictly homogeneous condition, and that rock magmas have really originated from what is often termed *refusion*, that is to say, from the melting down of all classes of pre-existing rocks.* We have the assurance of physicists that the earth is, to all intents and purposes, solid throughout; and as the great plutonic masses that we know have solidified at all periods since the earth has been influenced by present-day processes, it is equally evident that they must have formed at all periods, the melting down of buried portions of the crust being, of course, the only possible means by which this could take place, whatever the cause of the melting may have been.

MECHANISM OF REFUSION. The precise means by which refusion takes place is not perhaps a matter of immediate concern. We may, however, recall the fact that the earth's temperature is observed to increase as we go downward in mining and boring operations at the rate of about 1° C. for each 100 ft. of descent. If this rate of increase be granted as a reasonable one for even a small fraction of the earth's radius, it will be seen that at about 20 miles below the surface the temperature would be sufficient to cause the melting of almost any rock if there were nothing to counteract the increase. There is evidently a counteracting agency at work in the pressure of the overlying rocks. Anything which removed or even relieved this pressure would therefore tend to allow fusion to take place, and the arching up of the rigid strata above into an anticline might be quite sufficient. We also see that even if the observed rate of increase of

* For a fuller discussion of the problem see Papers read at the Joint Meeting of the British and South African Associations for the Advancement of Science, 1905, vol. ii., pp. 23-37; also Johnston-Lavis, *Geol. Mag.*, 1909, pp. 433-443, and Loewinson-Lessing, *ibid.*, 1911, pp. 248-257 and 289-292.

temperature continued indefinitely downward, relief of pressure could not cause fusion to an unlimited depth. The relief would only be operative as regards the rigid upper crust, and the column of liquid as it accumulated would eventually by its own weight suppress the tendency of the underlying materials to melt.

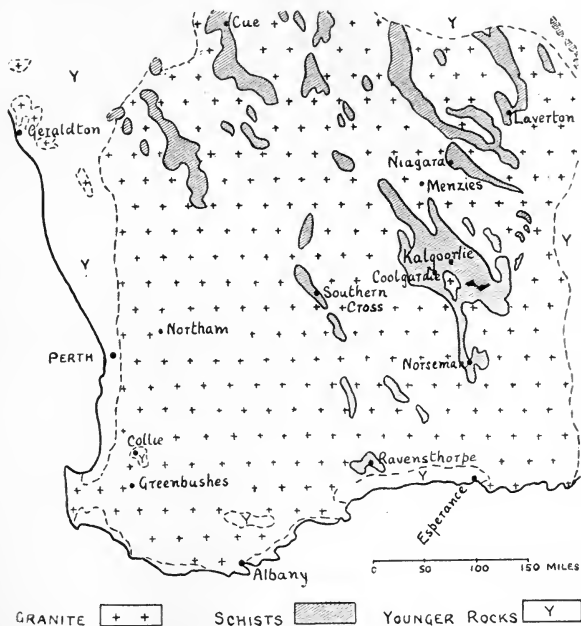


FIG. 56.—PART OF WESTERN AUSTRALIA, SHEWING GRANITE.

AVERAGE COMPOSITION. As a corollary of the "differentiation" theory, it is generally assumed that if all the igneous rocks be taken together, their average composition (and, by implication, that of the crust of the earth itself) would be that of an intermediate rock. Thus Mr. Clarke estimated the American rocks to average 59.77

per cent. of silica, and, following the same lines, Mr. Harker obtained 58.46 per cent. as his figure for the British rocks. This is the result, not of field work, but of the collation of analyses without taking into account the size of the rock exposures represented. A huge granite mass is thus allowed no more weight in forming conclusions than the most insignificant dyke or lava flow. Field work in areas where there are extremely favourable conditions, owing to the enormous development of igneous rocks, leads to very different results. The quantitative conclusions arrived at * from the mapping of a considerable area in Rhodesia are therefore of interest. It is found that, of twenty thousand square miles mapped, there are approximately 2,340 square miles of sandstone, 5,700 square miles of archæan schists, etc., and 11,960 square miles of granite and other igneous rocks. It will be seen that these last outbalance all the other classes put together. They comprise portions of a number of masses among which there are two developments of syenite (with about 63 per cent. of silica) covering some forty square miles. There is also an important intrusion of a pyroxenic rock which may be regarded as chiefly picrite, and containing on an average 45 per cent. of silica. The others, with a combined area of 11,680 square miles, are granites with a silica percentage probably averaging about 70 per cent. It must not be thought that there are few basic rocks; they are, on the contrary, well represented by dykes of dolerite and basalt flows. We shall, however, be making a generous allowance for them if we suppose there are 10,000 dykes a mile long and five feet wide, with 100 square miles of basalt twenty feet thick. We may further assume that these rocks contain about 50 per cent. of silica. There are a certain number of intrusions of porphyrite and orthophyre, but they are of less importance and may be reckoned as allowed for among the dolerites, whose volume may be subtracted from that of the granites in which they are commonly intrusive. We may then calculate the bulk of the respective classes as follows, on the basis of the plutonic and intrusive masses extending vertically downward as far as sea level only; that is, about one mile:

* See *Geol. Mag.*, 1904, p. 263, and 1909, p. 212.

Rock.		Silica per cent.		Area, sq. m.		Depth.		Volume, cub. m.
Granite	..	70	..	11,670	..	1 mile	..	11,670
Syenite	..	63	..	40	..	"	..	40
Picrite	..	45	..	240	..	"	..	240
Dolerite	..	50	..	nearly 10	..	"	} ..	
Basalt	..	50	..	100	..	20 feet	} ..	10
Total ..								11,960

We now multiply each silica percentage by the volume of the rock possessing it, the products then being added up and divided by the total volume. The result is an average of 69.45 for the whole. Whatever composition is assigned to the granites, the general average will, in fact, approach it within a few parts per thousand. We thus arrive at the conclusion that if all the other rocks of the area were to be fused into the granite masses the difference they would make would be quite imperceptible lithologically, and scarcely noticeable in a chemical analysis. Such a result would probably hold good for the entire African continent and certainly for the whole of Rhodesia. There is nothing to indicate that a different conclusion would be reached in any other extensive area where the plutonic rocks are adequately represented, and there is accordingly reason to believe that granite, instead of being one extreme of the igneous series, is substantially the average igneous rock, which amounts, indeed, to saying that it represents the average composition of the earth's crust.

If we accept the igneous rocks as having resulted from the melting down of previously solid materials, we see that these latter are very diverse, ranging from limestones, with down to 0 per cent. of silica, to sandstones with up to 100 per cent. By their complete admixture granite may evidently be produced, but where mixing depends to any extent on diffusion, heterogeneity would prevail for considerable periods of even geological time. When the conditions became favourable for eruptive activity, all grades of material would therefore be at hand, but owing to its greater fusibility and liquidity, basic material would be injected to greater distances, and be far more liable to reach the surface before consolidation, than the other classes, thus accounting for the great preponderance of

basic lavas over the other types. Owing to exhaustion of the basic material and to the mixing that would be a necessary consequence of the forces inducing extrusion, the lavas would tend to become increasingly acid, a fact which is often noted. At the same time fresh absorptions, due to fluctuations of pressure, might occur to produce a reverse effect, and we are not tied down to any particular sequence.

CIRCULATION OF MATERIAL. On the above basis it will be seen that there is constant circulation between the igneous and sedimentary rocks. Starting on the first formed masses of the cooling earth, the agencies of denudation have been constantly at work sorting the materials subjected to their action. Free silica has been separated unaltered from its associates, and formed into sandstones; felspar, altered, indeed, but not out of all recognition, has given rise to clays and shales; while the ferro-magnesian minerals, far more profoundly affected, have provided the materials for limestones and dolomites, as well as colouring and cementing material for rocks of all descriptions. Sedimentation, in fact, constitutes a very real analysis of the rocks on which the agencies of denudation are at work. The accretion of the plutonic masses is the very reverse. In its course the varied substances that have been so laboriously sorted out by mechanical and chemical agencies are melted down together, as it were, in one vast crucible: they are subjected to a very effective process of synthesis, and eventually cool down to become once more available for fresh sorting operations when anew cycle begins in its turn.

SELECTIVE ABSORPTION. The above is not, however, quite the whole story. There are various processes at work which tend to complicate matters considerably, and in a certain sense the idea of differentiation may be invoked to explain the production of particular rock types and associations of rocks. In the first instance, however, it is well to notice that the process of absorption is not always a simple one. To take an easily understood example of what is meant, the incorporation of limestones into a igneous magma is obviously complicated by the necessity for the elimination of their carbonic acid, and there can be little doubt that the so-called "magmatic water" connected with igneous intrusions is merely the normal water content of absorbed rocks expelled in a

similar way. The same idea is readily extended to the vapours which cause the formation of such compounds as tourmaline, topaz, scapolite, &c. But this is evidently not all. The process of *selective absorption*, as it may conveniently be termed, may even increase the complexity of the rock types to which it gives rise by the selection of some and the rejection of others among the non-volatile constituents of the masses incorporated in a magma. Thus in an instance brought forward by Harker * of an undoubted "hybrid" rock, there is much less lime shewn by analyses than would result from simple admixture—3 per cent. as against a calculated $4\frac{1}{2}$ per cent. It is rather curious, therefore, to note that Harker himself criticises the data so ably presented by Prof. F. D. Adams, with reference to the absorption of limestones, on the ground of there being too little lime in the resulting basic modifications of the invading granites. Limestones are evidently very insoluble in molten silicates, probably owing in part to their solution involving the displacement of carbonic acid by silica,† and much of their lime may tend to be removed by hydrothermal processes step by step with the rejection of water from a magma.‡ But limestones contain much more than lime,§ and their magnesia in particular seems to be taken up with greater facility, which may partly account for its abundance in basic rocks. This may also be compared with the so-called "dedolomitisation" which takes place in the contact alteration of so many dolomites. Magnesia evidently combines much more readily with silica and is likely, therefore, to be more readily transformed into normal igneous minerals.|| All rock con-

* Nat. Hist. Igneous Rocks, p. 358.

† The dissociation temperature of CaCO_3 is over 900°C , while the CO_2 is not driven off by simple heating when under sufficient pressure even at 1500°C .

‡ The amount in circulation is evidenced by the common replacement of serpentine and other magnesian silicates by dolomite rather than by magnesite.

§ See table of analyses in Chapter XIV.

|| The assimilation of lime seems to require the assistance of large amounts of the alkalies, or perhaps the removal of certain constituents like silica in conjunction with the lime causes an apparent increase of alkalinity, as Daly has suggested. Indeed, the field evidence points to the conclusion that most occurrences of rocks like "nepheline syenites" are almost to be regarded as metasomatic replacements of masses of limestone. Compare Adams, *Trans. Roy. Soc. Can. II*, p. 12, and Workman, *Geol. Mag.*, 1911, pp. 193-201.

stituents must, in fact, have different rates of solubility in a magma, while different magmas will conversely have different effects upon them. The recognition of this fact is essential in dealing with many problems of petrogenesis, and the idea of selective absorption will often help to clear up obscure points.

LIQUATION DURING REFUSION. While there can be little doubt that the assimilation of heterogeneous materials is one of the leading factors in the production of the various rock types, there are certain facts which seem to require for their elucidation the con-



FIG. 57A.—GRANITE XENOLITH, in Dolerite of Antelope Road, Rhodesia. $\times 20$ diam.—
(From *Geol. Mag.*)

ception of some sort of differentiation. For instance, the frequent occurrence of basic dykes penetrating granite masses of much greater age has been cited in a previous discussion of the subject of refusion* as an obvious "difficulty." It seems, however, to admit of a fairly simple explanation when we recall the fact that the minerals of a rock have very different melting points, the more basic ones being in general the easiest to fuse. They would, therefore, during the refusion of the rock in

* *Addresses etc., Joint Meeting Brit. & S.A. Assocs., 1905 p. 35.*

which they occurred, tend to melt first and might even liquefy out from the general mass. This was actually noted by Sorby in his experiments on the melting of the Mt. Sorrel granite.* A similar feature is to be observed in the case of the granite xenoliths in a dolerite dyke in the Matopo Hills, Rhodesia.† The ferro-magnesian constituent has entirely disappeared and become mixed with basic material from the dolerite, although the quartz, microcline, and oligoclase forming the bulk of the rock are only corroded to a greater or less extent. In another case, the granite adjacent to a dolerite dyke, east of the Umvukwe Hills in Mashonaland, was found to have its original ferro-magnesian constituent (probably hornblende) transformed into a finely granular aggregate of augite, enstatite, magnetite and a pale hornblende, the last quite different from the ordinary type occurring in granites (*see figure*). The rock is not otherwise appreci-

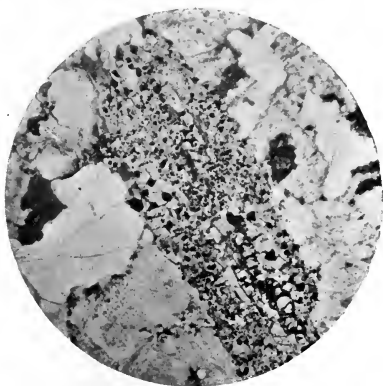


FIG. 57B.—GRANITE ALTERED BY DOLERITE.

ably changed, and the phenomena decidedly point to the fact that it was raised to a temperature just above the fusion point of hornblende and then rapidly cooled.

It seems that we have here a clue to the interpretation

* *Proc. Geol. & Poly. Soc. W. Yorks*, vol. iv, 1863, p. 301.

† *Geol. Mag.*, 1911, p. 14.

of phenomena which have been generally ascribed to purely hypothetical processes. Take the case of a long cooled granite consisting of quartz, felspar and hornblende and suppose it to be gradually depressed under a load of sediment to a position where the temperature slightly exceeds the melting point of the ferro-magnesian mineral.* The hornblende would undoubtedly melt without the other constituents being greatly affected, and, should any differential pressure be exerted on the mass, it might be squeezed out from the spongy solid residuum of the rock, of which it might carry away no more than a few detached and entangled grains. The composition of a dyke resulting from such a process might be that of the type which has been termed a basic "lamprophyre" and it would naturally tend to contain apparently foreign inclusions of the more acid felspars as such rocks often do.† The residuum would have the composition of an "aplite" or "pegmatite." If the hornblende were removed as indicated, and the temperature then increased sufficiently to permit the melting of the felspar, the resulting magma on extrusion might well consolidate as a "bostonite."‡ If, however, the melted hornblende substance still remained, on mingling with the felspar it would give rise to a magma which would reconsolidate as a perfectly normal augite andesite or basalt, as the well-known experiments of Messrs. Fouqué and Lévy have shewn.§ Entangled and corroded quartz granules, and the occurrence of patches and veins of micropegmatite, such as we see in many dolerites, &c., are again readily accounted for. From a normal mica-bearing granite, even the most

* The increase of temperature may be ascribed entirely to the normal rise of isogeotherms, or, as Prof. Joly would do, in great measure to radio-active processes, without affecting the question at issue.

† See Harker, *Petrology*, p. 153.

‡ In other words, what have been termed "complementary differentiation products" may easily arise in the manner that has been outlined. The process will be complicated by the tendency of mixed salts to melt at temperatures below the fusion points of the individual constituents of the mixture, but this does not appear likely to seriously disturb it.

§ *Synthèse des Minéraux et des Roches*, p. 78. It is interesting to notice what a suggestive sidelight this throws on Prof. Loewinson-Lessing's modification of the "two-magma" theory. See *Geol. Mag.*, 1911, pp. 248-257 & 289-297.

alkaline and basic rock types may be readily conceived as originating under the influence of liquation during refusion: indeed we need only recall in this connection the fact that Messrs. Fouqué and Lévy found that a mixture of biotite and microcline in nearly equal proportions re-consolidated after fusion as a crystalline aggregate of leucite, olivine, melilite and magnetite.* The highly magnesian character of the more basic rocks is also readily connected with the constitution of the basic silicates ("ferro-magnesian minerals") of granite masses.

VULCANISM. Although it was the study of the products of volcanic action that led to the recognition of the true characters of what we now confidently term igneous rocks, it is clear that vulcanism is by no means an inevitable concomitant of the production of molten magmas. At the same time, it seems evident that the lines of least resistance among the overlying rocks will always be sought out by a fluid magma, and when communication with the surface is established a volcano will tend to result, the more obvious features of which are, however, due to subsidiary causes. Theoretically, eruptive action might be expected to consist in the quiet and regular emission of lava through a fissure, and this simple condition is partly realised in the case of Mauna Loa and Kilauea. Such phenomena are probably much assisted by the surplus expansion (over that due to mere relief of pressure) which will necessarily result from the fusion of the previously solid materials constituting the magma from which the lavas are in the first instance derived. Practically, however, matters are usually much more complicated. The partial consolidation of the molten rock produces one set of complications, and the choking of the original fissure naturally results in confining the outflow of molten material to a single point, that where the resistance is least, and this

* In Rhodesia and also in the Transvaal there are great masses of nearly pure quartz (*e.g.*, the Inketa Kopjes near Bulawayo), associated with the granites which may represent a kind of ultra acid residuum from the liquation of parts of the masses on the lines referred to. It may be well to note here that the gneisses associated with apparently later granite masses are readily explained on the refusion idea, the latter being the perfectly fused and mixed materials, while the former have only been softened or at best imperfectly mixed. It will be seen that liquation further supplies an obvious reason why the acid variations are almost invariably intrusive in the basic modifications of a granite.

becomes the vent of the volcano. It is extremely doubtful whether the ideal condition of "fissure eruptions" has ever been completely realised. Moreover, it is fragmentary materials which are usually the most conspicuous feature of eruptions, and these are unquestionably the result of the explosive expansion of imprisoned water acquired at a great depth or encountered among the rocks near the surface. Some writers, indeed, are inclined to regard access of water to a magma as the prime cause of eruptive activity.* However, this may be, it is certain that the bulk of the volcanic piles themselves is generally built up of fragmentary materials, and in extreme cases, the energy generated may be sufficient to blow off the top

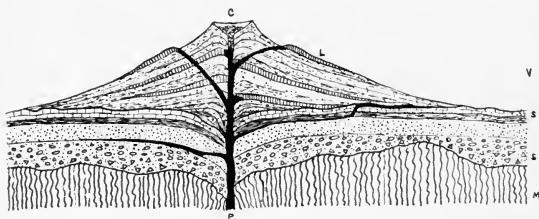


FIG. 58.—IDEAL SECTION OF A VOLCANO. L Lava. V Volcanic Tuffs, &c. SS Sedimentary Rocks. M Metamorphic Rocks. C Crater. P Pipe, through which lava, ashes, &c., rise to the surface.

of the volcano, as at Vesuvius in 1906, or even to scatter nearly the whole of it over the surrounding region as in the famous eruption of Krakatoa. Lavas are, in fact, a subordinate feature of many eruptions and in any case necessarily affect much more confined areas than materials like lapilli and ash. Thus though the tendency of lavas to rise to the surface is due to the deep-seated primary causes of eruptive activity, explosive manifestations are often a much more conspicuous feature of volcanic action, though they are, as Johnston-Lavis points out,† purely surface phenomena of a secondary character.

* See Arrhenius, *Geol. Mag.*, 1907, p. 173.

† *Sci. Trans. Roy. Dublin Soc.* Vol. IX, Series ii, 1909, p. 154. See also *Geol. Mag.*, 1909, pp. 433-443.

SEQUENCE OF ERUPTIONS. It was at one time pretty generally held, following the lead of Richthofen, that in most volcanic areas the liquid products of eruption usually succeeded each other in a definite order, that originally suggested, expressed in its simplest terms, being (1) intermediate, (2) acid, and (3) basic lavas. Further study has shewn that this, like so many similar generalisations, was based on wholly insufficient data. If



FIG. 59. COMPARATIVE OUTLINES OF THE GREAT CONE OF VESUVIUS BEFORE AND AFTER THE ERUPTIONS OF 1906. (After Johnston-Lavis.)

anything, increasing acidity is perhaps the most frequently observed tendency, but it is no more than a tendency, and in most volcanic regions it is certain that the sequence of eruptions shews no definite order of any kind. The following table of the eruptive sequence in the goldfield district of Nevada, as determined for mining purposes by F. L. Ransome, on behalf of the U.S. Geological Survey, will serve as a case in point:

* Formation.	Field Description.			Classification here adopted, where possible.
Malpais Basalt	..	Flow	.. ..	Olivine basalt, 48.20 % SiO ₂ in- cludes a mica and hornblende bear- ing var. 48.59% SiO ₂
Spearhead Rhyolite.		Flow or flows	..	Biotite hornblende pyroxene rhyolite
Nura Basalt	..	Flow	.. ..	Olivine basalt, with quartz
Espina Breccia	..	Roughly-bedded Dacitic Breccia		Andesite - rhyolite breccia
Meda Rhyolite	..	Flow	.. ..	Biotite rhyolite
Dacite Vitrophyre	..	Flow	.. ..	(See below)
Chispa Andesite	..	One or more flows		Augite andesite
Dacite Vitrophyre..		Flows	.. ..	Biotite hornblende andesite, with quartz, 59.99 % SiO ₂
Dacite	Intrusions, passing into flows and breccias		Includes : Augite hornblende biotite porphyrite, with quartz, 59.95 % SiO ₂ . Hornblende trachyte with quartz 61.25 % SiO ₂
Milltown Andesite	..	Mainly flows	..	Includes pyroxene- andesite 58.06 % SiO ₂ . Hornblende basalt 54.66 % SiO ₂ . Pyroxene trachyte 60.41 % SiO ₂ . Oli- vine basalt. Horn- blende biotite tra- chyte 63.16 % SiO ₂
Moreno Rhyolite	..	Intrusive masses	..	Biotite granophyre
Sandstorm Rhyolite		Flows	.. ..	Biotite rhyolite
Kendall Tuff	..	Lenticular deposits closely associated with Sandstorm Rhy.		Rhyolitic and andesitic tuff
Latite	Flow	.. ..	Biotite hornblende trachyte 61.14 % SiO ₂ . [rhyolite
Vindicator Rhyolite		Flow	.. ..	Much - altered

* See F. L. Ransome, *Geology and Ore Deposits of Goldfield, Nevada*, pp. 27-74.

THE EARTH'S INTERIOR. The geologist is not greatly concerned with the condition and constitution of the earth's interior, but volcanic phenomena have naturally caused a considerable amount of speculation on the subject. The rise of basic lavas from below rocks of an acid character, to which some attention has already been devoted, in conjunction with the high average density of the earth (5.5), has caused many authorities to assume that the earth's interior is of much more basic constitution than the crust. It has even been urged that it is the source of the heavy metals of our ore deposits, and that the earth possesses a nucleus largely consisting of metallic iron, the well-known characters of meteorites being cited as an additional point in favour of such a view. On this question we may well preserve a somewhat agnostic attitude. At the same time it must be noted that it is by no means a necessary conclusion that the composition of the earth's interior differs in any way from that of the surface, as it has been calculated that mere compression is quite sufficient to account for the core of the earth having a specific gravity exceeding 10, even if composed of materials similar to those of the exposed crust. Again, it is more than doubtful whether volcanic products give any clue to the composition of the interior of the globe: indeed eruptive phenomena appear to be purely superficial manifestations compared with the immense bulk of the earth. As regards physical state, the gradual rise of temperature with the depth which is invariably observed in mining operations (about 1° C. for each 100 feet) has led to a general acceptance of the theory that the earth is a cooling body with its interior still in a highly heated condition. At one time, indeed, there was a widespread belief that the crust was a mere shell floating upon still liquid materials. This idea was dispelled by the demonstration of Lord Kelvin and others that the whole globe shewed an extremely high rigidity, altogether incompatible with such a state of affairs, and the matter has been put beyond dispute by the fact that it acts as a solid mass in the transmission of earthquake shocks below the crustal zone. Even now there is a widely prevalent idea that a fluid stratum intervenes between the outer layer rendered solid by cooling and the interior kept solid by pressure.

Though this can scarcely be accepted in its crude form, it is evidently near the truth in the sense that at a depth of about twenty miles or so beneath the surface there commences a zone of matter at a temperature sufficiently high, and under pressure sufficiently low, to allow of easy fusion under the relieving influence of movements in the rigid masses above. That is to say, there is a zone of *potential* if not of actual fusion. It is evident, of course, that the normal pressure due to the mere weight of superincumbent material at any given depth must be *more than sufficient* to counterbalance the normal temperature increment. It is probable that the observed rate of increase near the surface does not hold good for any great distance downward. Indeed, considerable prominence has been given in recent years to conceptions which admit or even postulate a cold interior for the earth. Thus we have the planetismal hypothesis of Chamberlain and Salisbury which explains the earth as an accretion of cold meteoric matter and regards igneous magmas as due to mechanically generated heat near the surface. Radio activity also supplies another explanation of their formation without the necessity of internal heat, which has been enunciated by Prof. Joly. In these cases we have what appear to be agencies in actual operation as subsidiary factors, elevated into the position of prime causes. Mechanically generated heat and excessive local radioactivity may have some slight effect in promoting the temporary rise of isogeotherms, but it is scarcely necessary on this account to abandon such a well-established and apparently sound conception as that of the earth being a cooling globe.

CHAPTER X.

The Acid Igneous Rocks.

THE acid division of the igneous rocks comprises those types in which the silica percentage does not fall below 65. As this is the precise amount contained in orthoclase feldspar, it will be evident that any holocrystalline rock belonging to this group must contain free quartz, and the



FIG. 60.—GRANITE "KOPJE," in the Matopo Hills, Rhodesia.

greater the abundance of more basic silicates, the more quartz is required to justify its inclusion in this division. Any rock which has 20 per cent. of quartz may, however, be safely regarded as a member of it. In the cases where glassy or cryptocrystalline material is abundant, there may be no quartz, and in some instances chemical analysis alone can be relied upon for purposes of classification.

The specific gravity affords useful indications, and rarely rises as high as 2.4 in the glassy varieties. The granophyres range from about 2.4 to 2.6, while the granites generally lie between 2.6 and 2.7.

Quartz is of course the most characteristic mineral of the group, and makes up about one third of most normal types. *Muscovite* mica is also very characteristic, as it is rarely present as a primary constituent of any but thoroughly acid rocks. Its distribution is, however, very restricted and although almost confined to the plutonic types, it rarely occurs in large granite masses, except among the purely marginal modifications, though it may be found as an alteration product of the feldspars. Of these the potash-bearing varieties are abundant, both *orthoclase* and *microcline* being common. The latter is the dominant feldspar in many of the largest granite masses of the world and it may be readily recognised by the cross-hatching it always shews in polarised light. The plagioclases are also common and may be more abundant than the potash feldspars. *Albite* and *oligoclase* are the usual types.

It is not always easy to distinguish between orthoclase and oligoclase, as the latter is sometimes devoid of the twin lamellation that usually marks the plagioclase group, and, moreover, gives straight, or nearly straight extinction. Of the ferro-magnesian minerals, brown *biotite* is much the commonest in the plutonic and intrusive rocks; in the lavas *augite*, *hornblende*, and *enstatite* are of frequent occurrence, though the pyroxenes are very rare in the granites, while hornblende (always green) is only present in the more basic varieties. *Apatite* is an accessory which is rarely absent, while *zircon* is often met with, especially as an inclusion in the mica, where it gives rise to dark pleochroic "halos." *Magnetite* is sometimes present in small grains, while *sphene* is abundant in some occurrences. *Tourmaline* is often seen, especially in the dyke rocks, sometimes in beautifully zoned crystals, a blue centre with a yellowish margin being very characteristic. It always shews strong pleochroism, except in those rare instances where it is uncoloured. Of the rarer minerals *orthite*, or allanite, is found in yellowish brown crystals or grains, frequently zoned, and often intergrown with pale yellowish or colourless epidote, in which case it seems that

both must be regarded as primary constituents, especially as the epidote may be idiomorphic towards biotite. It is usually most conspicuous in the marginal modifications of the masses in which it occurs. *Andalusite* and *cordierite*, when present, may be regarded as derived from the recrystallisation of partly assimilated aluminous material. Pink or colourless *garnet* occasionally occurs in crystals or rounded grains, shewing marked relief and perfectly isotropic. *Topaz* is seen in a few granophyres, etc. *Rutile* is also found, and so is the isomorphous *cassiterite*. The



FIG. 61.—GARNET IN GRANOPHYRE,
Antelope Mine, Rhodesia. $\times 20$ diam.

former may be distinguished from sphene by its deeper colour, more marked pleochroism and stronger double refraction. Cassiterite is scarcely pleochroic, and its birefringence seems very variable, though always considerably weaker than that of rutile. As alteration products, *kaolin* may be seen clouding the feldspars, while *chlorite*, *calcite*, and *epidote* may arise from the decomposition of the ferro-magnesian constituents. The last-named may also result from the alteration of the lime-bearing feldspars, or interactions between them and the ferro-magnesian minerals. Its brilliant interference tints and pale colour, or want of it, serve to distinguish it from

sphene, which is usually brownish or dull yellow, and looks much the same in polarised as in ordinary light. Calcite is usually accompanied by granules of secondary quartz. *Chalcedony*, *opal*, calcite, chlorite, epidote, and various *zeolites* fill vesicles in the amygdaloidal volcanic members of the group. Stains of *haematite* and *limonite* frequently obscure the ground mass of the granophyres and rhyolites. Greenish yellow micaceous "pinite" pseudomorphs may replace cordierite. *Fluor* and *pyrites* may also be present, though the processes to which they owe their formation are somewhat uncertain.

GRANITES. These exhibit the even-grained structure of the plutonic rocks in the greatest perfection. Even the first-formed constituents seldom shew good crystal outline. Almost the only departure from simplicity that they shew are occasional little patches of micropegmatite, and a tendency to crystallisation of the quartz before microcline or orthoclase. A pseudo-porphyritic structure may be developed by the presence of relatively large crystals of felspar; it will be found, however, that these are nevertheless of later date than the associated ferromagnesian minerals, of which they frequently contain zonally distributed inclusions. Associated with most granites are many vein-like masses, usually of more acid composition than the normal rock, some of which are best considered in the next section. They consist as a general rule of quartz and felspar, with only small amounts of mica or other minerals, and are known when fine-grained as "aplite" and when coarse as "pegmatite." "Graphic granite" represents a type, usually of medium grain, shewing distinct intergrowths of quartz and felspar. Quartz-mica rocks (known as "greisen") may also be noticed in association with many masses, and seem generally due to the alteration of pegmatites by conversion of the felspar into secondary quartz and mica. As special accessories they may contain tourmaline, topaz, fluor, etc., and may even become of commercial importance by their content of cassiterite, wolfram, tantalite, etc. Occasionally they shew subordinate fresh felspar and seem to be primary (*see* previous chapter). Basic patches and streaks are often seen in granites. Attempts have been made to distinguish between them and obviously

foreign inclusions, but they really differ as a rule only in the amount of alteration they have undergone.

In some granites both biotite and muscovite micas occur, with quartz, orthoclase, and some plagioclase. These "two-mica" granites are well represented among those of Dartmoor (*e.g.*, Haytor, etc.), in which the plagioclase is often albite, sometimes intergrown with orthoclase, while tourmaline is constantly present, and inclusions of zircon are marked by the usual pleochroic halos in

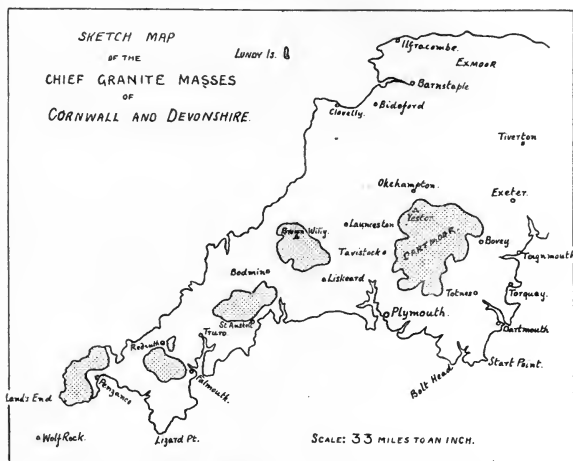


FIG. 62.—GRANITE MASSES OF CORNWALL AND DEVON.

the biotite. An interesting altered variety is that of Luxulyan in Cornwall, where tourmaline, in radiating needles, replaces the ferro-magnesian minerals and much of the felspar. The granite of Rubislaw, Aberdeen (69),* contains microcline, in addition to the other felspars, while in the Dublin granites (about 70) microcline entirely replaces orthoclase, as is so frequently the case in the larger masses.

* The figures in brackets in this and the following descriptions are the silica percentages of the rocks referred to in each case.

It is usually stated that the muscovite-bearing granites are of more acid composition than those with biotite alone. This is, however, far from being the case in the great Archæan areas of the globe. Biotite granites are, moreover, much more numerous than those with two micas, and the proposal to restrict the term "granite" to the varieties containing muscovite would exclude from the class all the most important masses in the world.' Thus those of the Laurentian areas of Canada are microcline-bearing biotite granites, sometimes with orthite as an accessory and considerable amounts of secondary



FIG. 63.—GRANITE, Matopo Hills,
+ nicols, $\times 30$ diam.

epidote. That of the typical Laurentian area in Ontario (77) is generally made up of orthoclase or microcline and oligoclase in nearly equal proportions, together with quartz, biotite and magnetite. The Matopo granite of Rhodesia is also a typical biotite granite of thoroughly acid composition, with microcline as the dominant felspar, and sphene, often accompanied by magnetite and orthite, associated as a rule with epidote, as accessories. This rock is strongly radio-active, no doubt largely owing to the orthite it contains. The great bulk of this immense mass is a uniformly fine and even grained rock, but close to its margins gneissose structures may frequently be

observed which were evidently assumed prior to complete consolidation. The "old granite" of the Rand (78½) is very similar to the Matopo rock. The granite of Cape Town is a coarse biotite bearing type. The felspar is orthoclase with a little intergrown plagioclase, while the biotite is deep red-brown, and intensely pleochroic. Apatite and zircon are accessories. Near the margin of the mass tourmaline is locally very abundant, the deep yellow or brown crystals being often zoned and edged with blue. Cordierite, often partly altered to pinite, is frequently observed. A good Australian example of this type is the granite of Cape Woolamai, in South Gippsland.

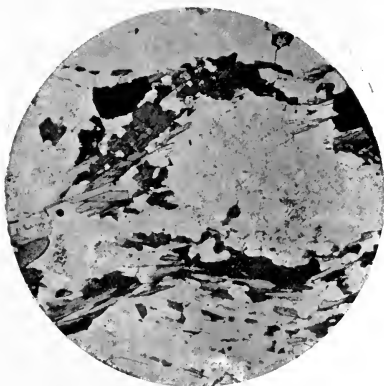


FIG. 64. GNEISSOSE MARGIN. MATOPO GRANITE. $\times 20$ diam.

It consists of orthoclase, oligoclase, brown biotite, and quartz, with apatite and zircon as accessories. The Shap granite of Westmoreland (68½) shews conspicuous crystals of pink orthoclase, and contains accessory sphene. The Rhodesian granites are rich in exceptional minerals. Thus we may note a biotite granite from Wankies which shews large pseudo-porphyritic crystals of orthoclase, and contains pink garnet, much yellowish-brown zoned orthite, and a blue isotropic mineral (? fluor), as well as apatite, magnetite, and zircon. An occurrence near the Jibuyi

River, in North Western Rhodesia, contains orthite in crystals averaging about 1 mm. in length, usually enclosed in epidote with the same orientation, which may, in turn, be idiomorphic towards the biotite. A specimen from the northern edge of the great granite mass stretching through North Eastern Rhodesia from Fort Jameson to near Tete, on the Zambesi, consists of microcline, oligoclase, quartz, biotite and garnet, with subordinate muscovite, and accessory orthite, apatite, magnetite, and zircon. Unlike the variety from Miask, in the Urals, familiar to European petrographers, the orthite of all these occurrences is very feebly pleochroic, and has a double refraction about equal to that of quartz. General MacMahon and Dr. Flett have recorded this interesting mineral from the granites of several Scottish localities, notably Fell Hill, in Kirkcudbright, Lairg, in Sutherland, Dalbeattie, and Hildesay.

The incoming of hornblende generally marks increasing basicity, and is often to be noted along the margins of masses that are free from it in their more central portions. The so-called "tonalite," or quartz-diorite of Adamello (67) really belongs to this group, and so do many others which have been termed grano-diorites, etc. The Mount Sorrel rock of Leicestershire, England, is another good example. Rocks of this type are very common in Australia; those of Swift's Creek (Vic.), Bathurst (66½), Moruya, Hillgrove and Hartley (N.S.W.) and of the Burdekin River, Mt. Morgan, Ravenswood, Charters Towers (67) and Bowen (Q) may be cited. The last two contain microcline, as does the well-known rock of Assouan, in Egypt (70). True granites with a pyroxene as the ferro-magnesian constituent are very scarce. The charnockites of India are largely enstatite granites, with microcline and oligoclase as the feldspars. A coarse-grained rock from Hillside, near Bulawayo, Rhodesia, consists of pale green augite, microcline-perthite, and quartz, with sphene as an accessory. It is a modification of the syenite of the locality. The Albany granite (72) of New Hampshire, in the United States, contains augite in addition to biotite and hornblende; while the granite of the Quincy quarries, near Boston, in Massachusetts (74) has aegirine and riebeckite as its ferro-magnesian constituents.

ANALYSES OF GRANITES.

	Biotite Granite, typical of Cana- dian Lau- rentian area (Norton Evans).	Two- Mica Granite, Lam- orna, Corn- wall (Pol- lard).	Two- Mica Granite, Mt. Leinster, Ireland (Haugh- ton).	Two- Mica Granite, Ogle- thorpe Co., Georgia (Wat- son).	Biotite Granite Shap, West- more- land (Cohen).	Horn- blende Biotite Granite, Bath- urst, N.S.W. (Min- gaye).
Silica ..	76.99	74.69	72.08	70.30	68.55	66.69
Alumina ..	12.45	16.21	14.46	16.17	16.21	17.03
Ferric oxide ..	1.03	trace	2.40	1.19	2.26	3.15
Ferrous oxide	.49	1.16	—	—	—	.69
Manganese oxide	trace	—	n.d.	n.d.	.45	trace
Lime ..	.98	.28	1.76	2.61	2.40	1.82
Magnesia ..	.21	.48	.10	.31	1.04	2.50
Potash ..	4.29	3.64	4.80	4.88	4.14	6.26
Soda .	3.46	1.18	3.01	4.72	4.08	1.21
Water. ..	.26	1.23	—	—	n.d.	.48
Etc. ..	—	.68	.91	.63	—	—
	100.16	99.55	99.53	100.81	99.13	99.83
<i>Specific gravity :</i>						
			2.63	2.66	2.69	2.85

ANALYSES OF GRANOPHYRES.

	Two Mica Grano- phyre, Esk- dale. (Dwerry- house).	Biotite Grano- phyre, Mourne Mts., Ireland (Haugh- ton).	Hyde Park Dyke, Butte, Mon- tana, U.S. (Stokes).	Arran "Pitch- stone," Scot- land (Player).	Augite Grano- phyre, Carrock Fell, Cumbld. (Bar- row).	Typical Drusy Grano- phyre, Skye (Pol- lard).
Silica ..	76.43	75.00	74.34	72.6	71.60	70.34
Titania ..	n.d.	n.d.	18	n.d.	n.d.	.46
Alumina ..	13.56	13.24	12.97	12.4	13.60	13.28
Ferric oxide .	.08	2.52	.61	.7	2.40	2.65
Ferrous oxide	.55	—	1.37	1.1	—	2.24
Manganese oxide	n.d.	n.d.	trace	n.d.	n.d.	.19
Lime ..	.03	.69	.85	.9	2.30	1.24
Magnesia ..	.54	—	.86	trace	.21	.40
Potash ..	4.72	4.33	4.72	4.7	3.53	4.90
Soda .	4.19	3.07	2.49	1.7	5.55	3.61
Water. ..	.82	—	2.14	5.2	—	1.22
Etc. ..	—	.80	.22	—	.70	—
	100.92	99.65	100.06	99.3	99.89	100.53

GRANOPHYRES. The acid intrusives dealt with under this head range from holo-crystalline varieties, closely related to the granites, to almost wholly glassy types. The former division may be distinguished from the truly plutonic rocks by the occurrence of more than one generation of the feldspars, by extreme fineness of grain, or by reversals of the normal order of crystallisation. Thus idiomorphic quartz characterises many types, while orthoclase may occur in porphyritic crystals as well as forming part of the general mass of the rock. In small intrusions one frequently finds crystals of quartz and feldspar, sometimes with, and sometimes without, a ferro-magnesian mineral, in a groundmass which often consists of quartz and feldspar, either in definite micrographic intergrowths or forming a fine-grained aggregate. In other cases, the groundmass may be cryptocrystalline (stony or spherulitic) or entirely glassy. An originally glassy groundmass is frequently found devitrified in the older rocks, and is not uncommon on the whole. In some instances there may be no phenocrysts, and the whole rock may consist of a finely granular aggregate of quartz and feldspar, often without ferro-magnesian constituents or possessing a micrographic or a spherulitic structure. Primary muscovite is very rare in the granophyres, while among the feldspars microcline is seldom met with. The accessories, like zircon and sphene, are for some reason rarely prominent, though in exceptional instances they may be abundant.

The types approximating to the granites are well represented as a rule in the neighbourhood of great granite masses ("aplites," "microgranites," etc.), and also in separate intrusions of some size. The Arran rocks (Scotland) shew both porphyritic and micrographic examples, while these are also well represented in Skye (70½) and in the Mourne Mountains of Ireland (75). In these cases, augite is the usual coloured constituent, as well as in the granophyres of Carrock Fell (67), Ennerdale (71½), and Buttermere, in the English Lake District. St. David's, in Wales, also supplies some good examples with micrographic and spherulitic structures.

Of Australian localities, Heathcote, in Victoria, provides some excellent examples of rocks with micropegmatitic

groundmasses, while spherulitic types are well represented near Carcoar, N.S.W. In the neighbourhood of Gwelo and Selukwe, in Rhodesia, hornblende-bearing granophyres occur with a groundmass shewing either micrographic or spherulitic structures in addition to a certain amount of granular quartz and felspar. In these instances the spherulites can be resolved under high powers into definite radially-arranged micrographic intergrowths of the last two minerals, and all gradations can be studied between the spherulitic and micro-pegmatitic structures. Very similar rocks occur in the Matopo Hills in associa-



FIG. 65.—COMPOSITE GRANOPHYRE,
Matopo Hills. + nicols, \times 20 diam.

tion with dolerite dykes, and it can be clearly seen that they are due to the melting and impregnation of the adjacent granite by the basic intrusions.* This explanation will probably apply to most instances of the frequently observed association of granophyres with gabbro or dolerite,† especially as the process need not have taken place where these rocks are now observed *in situ*.

The well-known marble-like muscovite-bearing rock of Meldon, near Okehampton, in Devon, is of special interest

* *Geol. Mag.*, 1911, pp. 10-15, and plates.

† G. Tyrrell, *Geol. Mag.*, 1909, pp. 363, etc.

as containing a colourless, as well as a strongly pleochroic variety of tourmaline, and also topaz. It is now quarried for china-stone. Some dykes of this class contain garnet. This is the case near Dublin, also at the Antelope Mine and in the Shangani and Charter districts of Rhodesia. These latter are rich in plagioclase and very even grained, though they grade into pegmatites, &c. Another Rhodesian rock of this class, from the Dupoji River, Wankie district has both garnet and tourmaline, a very rare association. It is coarser but less even grained than the preceding types, contains abundant microcline, and micropegmatite is present.

The dykes of Devonshire and Cornwall provide typical

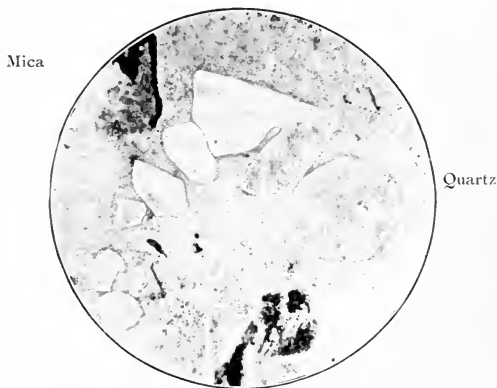


FIG. 66.—GRANOPHYRE OR QUARTZ PORPHYRY.
Penhale Moor, Cornwall. $\times 30$ diam.

examples of what are perhaps the most abundant forms of granophyre, namely, those with quartz and felspar phenocrysts set in a finely microcrystalline or "stony" groundmass. One from Lostwithiel shews much idiomorphic quartz and orthoclase, with some tourmaline, but no normal ferro-magnesian constituent, in a microcrystalline groundmass. A similar rock from Penhale Moor has phenocrysts of decomposed biotite in addition to the quartz and orthoclase. The well-known "porphyry,"

which occurs as boulders in the New Red breccias at Teignmouth, in Devonshire, has phenocrysts of corroded quartz and somewhat altered perthitic orthoclase, as well as small flakes of much altered biotite, in a stony groundmass, with small lathshaped feldspars and biotite flakes of a second generation. In rocks of this class microcline phenocrysts are not often seen: they occur, however, in several intrusions near Bulawayo, and elsewhere in Rhodesia and Bechuanaland. An enstatite-bearing granophyre occurs at Grimma, Saxony. It has a finely microcrystalline groundmass with quartz, feldspar, biotite, and

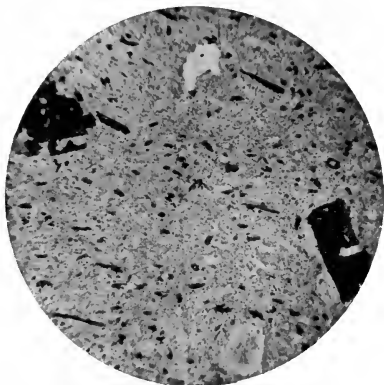


FIG. 67.—BIOTITE GRANOPHYRE. Teignmouth.
× 30 diam.

enstatite phenocrysts, sphene, apatite, and magnetite being the accessories. Another enstatite-bearing rock of this type comes from the Wollondilly River, N.S.W. (66). Ægirine occurs in granophyres from Christiania, in Norway, Inchnadampf, in Scotland (75), the Black Hills of South Dakota, and Mount Macedon in Victoria. A very interesting rock of this class occurs at Rockall (73½) in the Atlantic. Judd describes it as containing green ægirine bordered by brown acmite as its first crystallised constituent with albite and quartz making up the remainder of the rock. Secondary riebeckite is sometimes developed.

Riebeckite has been recorded as occurring in the granophyres of Mynydd Mawr, Carnarvon, and of Ailsa Crag and elsewhere in Scotland, as well as at Rhode Island, U.S. (73), while glaucophane is also found at various localities in the United States. Among altered types it may be noted that granophyre dykes associated with tin or wolfram lodes are often rich in topaz or tourmaline. "Schorl rocks" are common in Cornwall, while at Mount Bischoff, Tasmania, and Watsonville, Queensland, there are rocks of which the whole bulk has been replaced by radiating aggregates of topaz crystals (*see* fig. 40).



FIG. 68.—GLASSY GRANOPHYRE. Arran.
× 60 diam.

Of those granophyres which are partly or wholly vitreous ("pitchstones"), the island of Arran provides classic examples. The Corriegills rock ($72\frac{1}{2}$) contains fern-like skeleton crystals of hornblende surrounded by clear spaces set in a deeper coloured glass. Occasional phenocrysts of felspar and augite occur. Devitrification gives rise to some remarkable spherulitic types. The glassy character of these and similar rocks, it may be remarked, appears to be correlated with the retention of occluded water, a fact which is revealed by analyses in a striking manner and appears quite at variance with the prevalent

idea that water assists the crystallisation of quartz and the acid felspars.

RHYOLITES. In marked contradistinction to the enormous preponderance of the plutonic rocks of acid composition, these are apparently the most restricted in occurrence of all the various types of lavas. The glassy varieties called "obsidian" and "pumice" are best known, and are nearly all products of recent volcanic activity. They often contain no phenocrysts, but, on the other hand, frequently shew very interesting developments of crystallites, especially along lines of flow. Perlitic cracks are commonly seen, beautiful examples coming from Saxony and Mexico, and the structure may often be detected in devitrified types dating back even to the Archæan period.

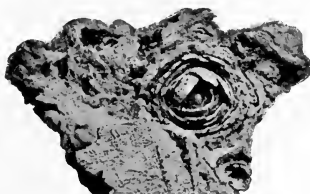


FIG. 69.—LITHOPHYSE.

Spherulitic structures are frequently developed in these rocks by devitrification, either during the original cooling of the rock, or owing to subsequent alteration. Where porphyritic structures are seen, the groundmass may be glassy or shew signs of having been so, though now cryptocrystalline. If crystalline, the grains composing it are always very minute. Flow structures are frequently marked by differences of colour and texture in alternate bands, or by linear groupings of crystallites and microlites. A feature specially characteristic of the rhyolites is the occurrence in certain of them of the peculiar contraction cavities known as *lithophyses*. These may contain exceptional minerals, like olivine, topaz, and tridymite, not found in the general mass of the rock.

The well-known *obsidian* of Vulcano, in the Lipair

Islands (72), affords a good example of an almost perfectly glassy lava. It only shews a sprinkling of magnetite dust and very minute crystallites, occasionally clustered along lines of flow. The Tertiary lavas of the Hauraki district in New Zealand include many interesting rhyolites. Others are recorded from Cowra and Bathurst, New South Wales. The early Tertiary lavas of Antrim in Ireland also include examples of glassy and devitrified as well as lithoidal rhyolites. That of Sandy Braes has perlitic cracks, sometimes affecting phenocrysts as well as glass, while that of Cloughwater is almost entirely made up of rows of small spherulites exhibiting very perfect black crosses in polarised light. Some of them coalesce into what Zirkel has termed

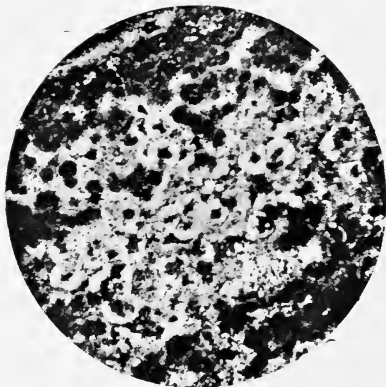


FIG. 70.—SPHERULITIC RHYOLITE.
Cloughwater, Antrim. —+— nicols,
× 30 diam.

axiolites. There are signs of secondary silicification, but no true phenocrysts. In Scotland there are few acid lavas of Tertiary age, but representatives of this division appear to occur in Skye. Some of the so-called trachytes of the Auvergne region are rhyolites with cryptocrystalline groundmasses. From the Black Hills of South Dakota, Caswell has described various rhyolites with abundant phenocrysts. Iddings has redescribed some of these as

dacites, but they are of typically acid composition. Similarly the well-known rock of Lassen Peak in California has a silica percentage of 69.3. The Hungarian Tertiary rhyolites have often been described; they are usually rich in quartz and felspar phenocrysts and have biotite as the principal coloured constituent. The Permian "pitchstones" of Meissen in Saxony ($73\frac{1}{2}$) are rhyolites, usually with quartz and felspar phenocrysts in a brownish glassy groundmass, shewing occasional development of

ANALYSES OF RHYOLITES.

	Biotite Rhyo- lite, Tard- ree, Antrim	"Neva- dite," Chalk Mtn., Color- ado	"Per- lite," Hlinik, Hun- gary	Horn- blende- Py- roxene Rhyo- lite, Crater Lake, Oregon, U.S.	"Da- cite," Lassen Peak, Cali- fornia	Horn- blende "Da- cite," Shasta Co., Cal.
	(Player).	(Cross).	(Ram- mels- berg).	(Stokes).	—	(Riggs).
Silica ..	76.4	74.45	73.00	71.87	69.51	68.10
Alumina ..	14.2	14.72	12.31	14.53	15.75	15.50
Ferric oxide .	1.6	none	2.05	1.28	3.34	3.20
Ferrous oxide	—	.56	—	1.02	—	none
Manganese oxide	n.d.	.28	n.d.	—	—	trace
Lime.. ..	.6	.83	1.20	1.59	1.71	3.02
Magnesia ..	—	.37	1.47	.48	2.09	.10
Potash ..	4.2	4.53	5.96	2.84	3.34	3.13
Soda . . .	1.8	3.97	1.36	5.08	3.89	4.20
Water. . .	1.5	.67	2.90	.28	—	2.72
Titania ..	—	—	—	.41	—	.15
	—	—	—	.25	—	.09
	100.3	100.38	100.25	99.63	99.63	100.21

perlitic and spherulitic structures, and alteration along the cracks. The Devonshire lavas of like age include rhyolite, near Thurlestone, associated with tuff, but in a less fresh condition. They have a crypto-crystalline groundmass, and phenocrysts chiefly of quartz, often much corroded. Rhyolites of Devonian age occur in the Western Highlands of Scotland. The Ordovician lavas of Wales, Ireland, and the English Lake District include various

types of rhyolite, usually with few phenocrysts, among which plagioclase felspars are commoner than orthoclase. In spite of much alteration, the Archæan lavas exhibit most of the structures of more recent types. Some with spherulitic groundmasses are found as pebbles in the Torridonian rocks of the North-west Highlands of Scotland. The Lea Rock (72) affords an English example with occasional phenocrysts of oligoclase. The large nodular spherulites may be original, but the microgranitic structure of the intervening areas is obviously secondary, as they are traversed by well-marked perlitic cracks. Very similar ancient rocks occur in South Africa, *e.g.*, at Kimberley in Cape Colony, at Gaberones in Bechuanaland, and at Gatling Hill in Rhodesia.

CHAPTER XI.

The Intermediate Rocks.

WE now come to the consideration of the sub-acid and sub-basic igneous rocks. These two classes may be taken together for descriptive purposes ; indeed, it is regrettable that usage prevents us conveniently uniting them in our classification. There is a good deal to be said for the practice of some authors in calling all intermediate plutonic rocks with dominant orthoclase, syenites, and classing those rich in plagioclase as diorites. Even supposing that the rock occurrences were equally distributed among the various types, the restriction of their silica percentages would make this class a smaller one than the acid group already treated of, and, as it is, they assume quite an insignificant position in comparison with it. In fact, those rocks which have been so generally, but, as we believe, erroneously, regarded as more or less representing the average magma, are of much more limited distribution than even the basic types, though they include a certain number of masses which are less equivocally plutonic than any basic rock.

The characteristic minerals of the group are *hornblende* among the ferro-magnesian constituents, and *oligoclase* or *andesine* among the feldspars, though as phenocrysts in the hypabyssal and effusive types, the *pyroxenes* are very common, and more basic feldspars often observed. Indeed, there is less uniformity in these rocks than in any other group.

Primary muscovite is scarcely ever seen, and quartz is rare, much rarer than is often imagined, for many so-called "quartz diorites," the well-known rock of Tonale, for example, are merely granites, with no greater departure from the normal types than a rather large amount of plagioclase. In the case of the syenites, it should be remembered that, as their silica percentage is that of ordinary orthoclase feldspar, the presence of quartz in

more than insignificant amount requires to be counter-balanced by the presence of a good deal of a more basic felspar, or more than the ordinary proportion of the ferromagnesian minerals. And, further, in rocks so basic as the diorites, where the quartz would have to be set off against a great predominance of very basic minerals, its presence in the face of what is often termed mass action is unlikely, though, in a non-plutonic rock, the fact that the crystallisation is often by stages greatly reduces the difficulties, and micropegmatite does, in fact, often occur. There can be no doubt, however, that, as Prof. Cole and others have pointed out, many so-called diorites, especially quartz diorites, are really of contact metamorphic and "mixed" origin. The feldspars are of great assistance as a criterion. Thus, it is hardly to be supposed that a rock in which microcline and labradorite both occur can possibly have consolidated from fusion under plutonic conditions, so that we are compelled to ascribe it to a metamorphic origin. Chemical considerations like this are invaluable in coming to a decision in doubtful cases.

In specific gravity the syenites usually range from 2.7 to 2.8, and the diorites from 2.8 to 2.9. The related lavas and dyke rocks are, as a rule, a decimal or so lower.

In the syenites, richness in the alkalis usually expresses itself by abundance of alkali feldspars, either *orthoclase* or *microcline*, the latter being by no means uncommon, and by the presence of soda among the bases of the ferromagnesian constituents, a yellow to green pleochroic *augite* being often noted. In the diorites, the feldspathoid minerals rise into importance. *Nepheline*, rarely seen in the true syenites, may be abundant, while *sodalite* is also sometimes noticed. None of the other feldspathoids seem to occur in what may fairly be termed plutonic rocks; most of the types rich in such minerals must be classed either with the basic or ultra-basic intrusions and lavas. *Hauyne* and *nosean* are, nevertheless, found in some andesites and porphyrites, nearly always accompanying nepheline. The true trachytes and orthophyres very rarely carry feldspathoids at all. The student may be reminded that these minerals are as basic as olivine. They in no way correspond to the feldspars in their chemical relations, and in the vast majority of cases they occur in

thoroughly basic rocks, though these last are nevertheless styled "syenites" by many writers.

ANALYSES OF SYENITES.

		Biotite Syenite with micro- perthite, Mon- mouth, Ontario (Norton Evans).	Quartz Syenite ("Tona- lite"), Wistra, Carin- thia (Krez- mar).	Quartz Syenite ("Bio- Gran- ite"), Dorsey's Run, Md. (Hille- brand).	Augite Horn- blende Syenite, Yogo Peak, Mon- tana (Hille- brand).	Hyper- sthene Quartz Syenite, Milam's Gap, Va. (Phalen).	Syenite, Plauen- scher Grund, near Dres- den. (Merrill)
Silica	..	64.15	63.09	62.91	61.65 TiO ² .56	60.52	60.02
Alumina	..	19.04	18.89	19.13	15.07	16.99	16.66
Ferric oxide		1.02	3.48	.98	2.03	.60	7.21
Ferrous oxide		.93	2.02	3.20	2.25	6.53	7.21
Manganese oxide		.16	n.d.	—	.09	.25	n.d.
Lime...	..	1.37	6.18	4.28	4.61	4.58	3.59
Magnesia	..	.37	1.97	1.69	3.67	1.59	2.51
Potash	..	7.10	1.30	3.38	4.50	3.91	6.50
Soda	..	5.37	3.14	3.94	4.35	2.83	2.41
Water.	..	.27	.63	.63	.67	.88	1.10
Phosphoric acid		.10	—	—	.33	—	—
Carbonic acid		.70	—	—	BaO .27 SrO .10	—	—
		—	—	—		—	—
		100.58	100.70	100.14	100.15	99.42	100.00

We have already remarked on the fact that hornblende is the characteristic ferro-magnesian mineral, but this scarcely holds good in the case of the trachytes, and especially the andesites. The latter are generally pyroxene-bearing, *enstatite*, as well as augite, often occurring, while *biotite* is found more particularly in the trachytes. In no rocks is the porphyritic structure more conspicuous, nor the successive stages of crystallisation better shewn, than in the andesites, porphyrites and trachytes, though all are occasionally quite free from phenocrysts, and the first sometimes approximate to the basalts in appearance. Glassy and "stony" groundmasses are rarer than among the acid rocks. They are much more commonly made up of crystals, minute indeed, but quite recognisable as belonging to their particular species.

Accessory minerals, for reasons that are not very obvious, are extremely numerous in many of these rocks, especially the syenites. *Sphene* and *zircon* are often very abundant; also *apatite*, while *magnetite* and *ilmenite* are constantly present. To find all the above in a syenite is by no means uncommon. The *tourmaline*, *andalusite*, *orthite*, *garnet*, and *cordierite*, which sometimes occur in the granites, are very rarely seen—the two first scarcely ever. *Epidote*, *chlorite*, and occasionally fine flakes of *muscovite* may be abundant as alteration products;

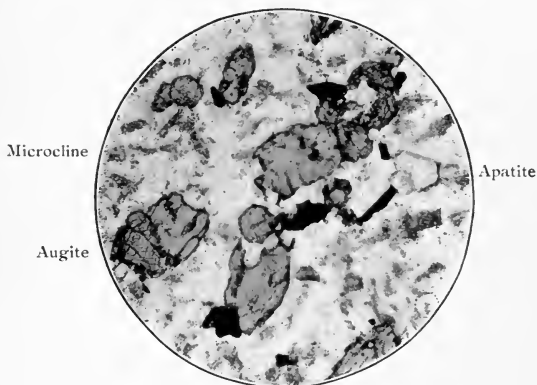


FIG. 71.—AUGITE SYENITE. Waterworks, Bulawayo, Rhodesia. $\times 30$ diam.

calcite, *kaolin*, *quartz*, and *zoisite* being also common, while *fluor* at times occurs, and is liable to be mistaken for *sodalite*.

SYENITES. The rock which is generally quoted as the typical syenite is that of the Plauenscher Grund, near Dresden. This is a marginal modification of the Meissen granite, and belongs to the basic extreme of the group, containing about 60 per cent. of silica, the best known analysis giving even less. It consists of orthoclase, some oligoclase, and hornblende, with accessory sphene and apatite, and often some subordinate quartz. Similar

rocks occur in Piedmont, Italy. True syenites occur associated with more basic alkaline rocks often containing nepheline, in Eastern Ontario. One, described by Prof. Adams from the township of Monmouth (64), consists almost entirely of microperthite, with a small amount of biotite, a little muscovite and calcite being also present. This occurs on the margin of a granite mass, which is indeed the common mode of occurrence for such rocks. Thus the grey marginal modification (61) of the Ben Nevis granite, in Scotland, is evidently to be regarded as a quartz-syenite. A remarkable pyroxene-bearing quartz, syenite is described by Phalen from Milam's Gap, Virginia, U.S.A. (60½). It consists essentially of orthoclase and plagioclase with both rhombic and monoclinic pyroxenes (hypersthene and diallage). There is subordinate quartz and microcline, with accessory magnetite, apatite and zircon, as well as secondary epidote, chlorite and sericite. A more normal American quartz-syenite is that of Dorsey's Run, Maryland (63) which has biotite as its ferro-magnesian constituent and sufficient quartz to be generally known as "biotite-granite." An interesting and perfectly quartz-free syenite occurs as independent intrusion about 15 square miles in extent at Hillside, near Bulawayo, Rhodesia (63½). The felspar is microcline, sometimes with subordinate oligoclase, generally forming an aggregate of mutually interfering crystals in which the ferro-magnesian minerals are scattered about. The most abundant of these is a noticeably pleochroic augite (pale green to yellowish), often idiomorphic in the prism zone, with which is usually associated a strongly pleochroic hornblende (deep bluish to pale yellowish-green). As accessories, sphene, apatite, and magnetite (titaniferous) are abundant, while zoned zircons are also seen, as well as secondary epidote, and sometimes calcite. Varieties are found in which hornblende almost entirely replaces the augite, and others in which biotite becomes prominent; while in others the microcline forms large plates enclosing the remaining constituents in poecilitic fashion.

ORTHOPHYRES. Good examples of sub-acid intrusions are not very easy to find. One given off as a large dyke from the syenite described above has big porphyritic crystals of andesine and orthoclase, and

occasionally small corroded quartzes, in a minutely crystalline groundmass. Such a mineralogical constitution is strikingly different from that of the parent mass. Some of the intrusions of the Charnwood Forest in England should no doubt be classed here, *e.g.*, that of Croft Hill (64). The well-known "red antique porphyry" of Djebel Dokhan, Egypt (64), shows opaque ferruginous pseudomorphs after hornblende, and cloudy feldspars in a microcrystalline groundmass. The interesting manganese-bearing epidote withamite is quite abundant as an alteration product, and exhibits its striking pleochroism, (α)

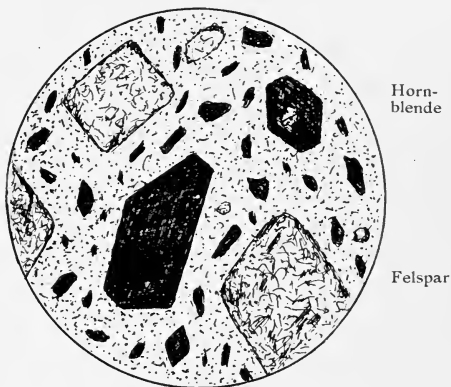


FIG. 72.—"ROSSO ANTICO PORPHYRY." Djebel Dokhan, Egypt. $\times 20$ diam.

yellow, (β) light pink, (γ) pink. The "Nordmarkites," or "quartz-syenites," of Christiania, Norway (64), and of Brome Mtn., Quebec (62) should be included among the orthophyres. The handsome "Canisp porphyry" of Sutherland also probably belongs here. According to Teall it has large phenocrysts of oligoclase and orthoclase, together with ægirine-augite and biotite, embedded in a microcrystalline groundmass of feldspar and quartz. The other sub-acid rocks of the district all contain hornblende. Professor Gregory has described as trachy-phonolites some remarkable richly alkaline members of this group

from Mount Macedon (Vic.), Australia (62½). They show large phenocrysts of anorthoclase in a groundmass of laths of the same mineral together with a little glass, through which are also scattered small crystals of ægirine, nosean, and ilmenite. Associated with these are other intrusions (64) with labradorite and hypersthene phenocrysts in a groundmass of oligoclase and quartz with abundant ilmenite. The Carboniferous intrusions of the Garlton

ANALYSES OF ORTHOPHYRES AND TRACHYTES.

	Glassy Augite Ortho- phyre ("Pitch- stone"), Barnes- more Gap, Donegal	"Quartz Syenite Por- phyry" or "Nord- markite," near Christi- ania, Norway	"Bio- tite En- statite Dacite" (Ortho- phyre), Upway, Vic., Aus- tralia	Biotite Trachyte, Dike Mount- ain, Wyo- ming	Biotite Augite Tra- chyte, Clover Meadow, Cali- fornia	Horn- blende Augite Biotite Tra- chyte, Hlinik, Hun- gary
	(Haugh- ton).	(Brög- ger).	Rich- ards).	(Hille- brand).	(Hille- brand).	(La- gorio).
Silica ..	64.04	64.04	63.27	63.24	62.33	62.54
Titanium oxide	n.d.	.62	1.30	.38	1.05	n.d.
Alumina ..	10.40	17.92	16.50	17.98	17.30	} 23.56
Ferric oxide .	} 9.36	.96	.68	2.67	3.00	
Ferrous oxide		2.08	5.10	.85	1.63	
Manganese oxide	—	—	.03	.04	.08	n.d.
Lime.. ..	4.24	1.00	4.18	.93	3.23	4.75
Magnesia ..	—	.59	2.48	.63	1.62	1.15
Potash ..	3.63	6.08	2.68	5.47	4.46	2.43
Soda . . .	2.91	6.67	2.36	6.27	4.21	3.16
Water. . .	—	1.18	.61	1.17	1.19	—
Etc. . . .	5.13	.23	.31	.51	.80	1.75
	99.71	101.37	99.50	100.14	100.33	99.34

Hills, in the south of Scotland, include sub-acid types with orthoclase phenocrysts. They are uncommon among the Tertiary rocks of Great Britain and Ireland. Prof. Sollas, however, describes glassy types (64) forming small dykes in granite at Barnesmore Gap, Donegal. These, though more basic are very similar to the Arran "pitchstones," but contain skeleton crystals of augite and magnetite instead of hornblende. They have augite and orthoclase

phenocrysts and merge into more crystalline varieties. The well-known rock of the Sgurr of Eigg (63½) is another glassy member of the present group.

TRACHYTES. A considerable number of the rocks usually classed as dacites and trachytes are really rhyolites, this being the case with the rock from the Drachenfels in the Siebengebirge, often regarded as a sort of type. Some of the so-called andesites, on the other hand, really belong here. Thus some of the augite-bearing lavas of Cotopaxi have about 64 per cent. silica. Bonney describes another from the summit of Aconcagua with a silica percentage

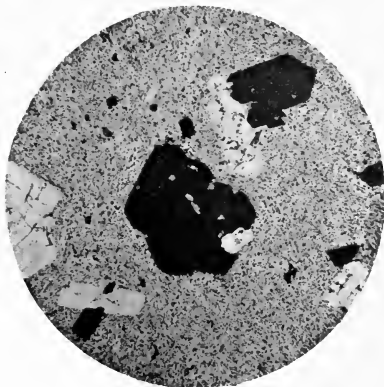


FIG. 73.—BIOTITE TRACHYTE, Mt. Dore.
× 20 diam.

just over 60. Glassy sanidine trachytes occur at Monte Somma and Teneriffe. An Ordovician pyroxene trachyte occurs at Brown Knotts, near Keswick (61). Hyperssthene trachytes have been described from Mount Shasta, California (62) and Carhope in the Cheviots (61), the former being of Tertiary and the latter of Old Red Sandstone age. Tertiary hornblende trachytes occur in the Siebengebirge and in the Auvergne region. One of the few feldspathoid-bearing trachytes occurs in the latter area, the "phonolite" of La Tuillere, Mont Dore (61). On Mont Dore there occurs a very good example of mica trachyte (*see*

figure) with biotite in large flakes, and occasional crystals of pale greenish augite or brown hornblende. There are large oligoclase phenocrysts, while the ground-mass is a very fine grained aggregate of felted felspars speckled with magnetite. The British Tertiary lavas include few representatives of the sub-acid division; they have, however, been recorded by Harker from the Cuillin Hills in Skye. Trachytes and more basic rocks of an alkaline character, sometimes containing nepheline, have recently

ANALYSES OF DIORITES.

	Diorite, Wyalong, N. S. W., Australia	Mica Diorite, Crystal Falls, Michigan, U.S.	Diorite, Butte Co., California, U.S.	Augite Diorite, ("Akerite"), Christiana, Norway	Mica Diorite, with Albite and Microcline, Craigmont, Ont., Canada	Nepheline- Sodalite Diorite ("Ditroite"), Transylvania (Fellner).
	(Watt).	(Stokes).	(Hillebrand).	(Kjerulf).	(Connor).	
Silica ..	58.93	58.51	57.87	56.79	56.05	56.30
Titanium oxide	.52	.72	.53	n.d.	.47	n.d.
Alumina ..	17.48	16.32	16.30	16.64	17.02	24.10
Ferric oxide	1.73	2.11	1.71	} 9.58	9.10	} 1.99
Ferrous oxide	5.01	4.43	3.86		4.20	
Manganese oxide	Trace	Trace	.08	n.d.	.08	n.d.
Lime.. ..	7.08	3.92	5.53	5.12	.72	.69
Magnesia ..	4.33	3.73	5.50	2.63	.12	.13
Potash ..	1.34	4.08	.75	2.55	5.12	6.79
Soda ..	2.91	3.11	5.01	5.30	6.10	9.28
Water ..	.86	2.23	2.66	1.27	.36	1.58
Etc. ..	.14	.30	.32	—	.04	—
	100.33	99.46	100.12	99.88	99.38	100.86

been described from East Lothian (Haddington) by the Geological Survey.

DIORITES. Examples of these come from Charnwood, in Leicestershire. They are composed of hornblende and plagioclase, probably andesine in most cases, with subordinate biotite and quartz, accessory apatite and magnetite and a little secondary epidote and pyrites. Very similar rocks occur as modifications of granite masses all over the

world, and that they originate from the absorption of masses of basic schist can often be demonstrated. In the hornblendic granite of Bulawayo, in Rhodesia, such types form large bands and patches, sometimes nearly free from quartz. The hornblende is bluish green and seldom idiomorphic, while the feldspars usually include oligoclase and microcline. Flakes of biotite sometimes occur. Brownish sphene and apatite are abundant accessories, and near the edges of the plutonic mass bright yellow epidote occurs with all the appearance of an original constituent. A true quartz-diorite (59) occurs at Wyalong in New South Wales. It consists of oligoclase and hornblende with subordinate quartz and biotite:

More alkaline types are represented by such rocks as those associated with the syenite already described from Hillside, near Bulawayo. The most normal of these have oligoclase as the dominant feldspar, though there is also a good deal of microcline. Hornblende is the ferro-magnesian constituent: it often shows a core of augite. Well-developed crystals of sphene are abundant, while magnetite and apatite are other accessories. Further examples have microcline as the dominant feldspar, with very abundant alkali-augite as the ferro-magnesian constituent, the latter being often set in poecilitic fashion in the large feldspars or clustered round their edges (*see* fig. 48). In other cases, augite and biotite may be present in about equal amount, or augite, hornblende, and biotite may all occur together. Sphene and apatite are always abundant as accessories, sometimes accompanied by zircon and secondary epidote. The rock (57) termed "Laurvikite" by Brögger is very similar to the above. The so-called ditroite of Transylvania (56½) is also obviously closely allied to types like these. It is composed of microcline with quite subordinate plagioclase, but sodalite and sometimes nepheline are also present. The ferro-magnesian minerals are very sparingly distributed: they are augite (acmite), hornblende, and biotite. Magnetite, apatite, and sphene are accessories, while calcite and cancrinite appear as alteration products. The so-called "augite-syenite" of Groba, Saxony, is also a mica-augite-diorite, with andesine and orthoclase feldspars and abundant accessory magnetite. At Frontino, in the United States

of Colombia, occurs a very similar rock, but with more plagioclase, which shews a tendency to form elongated crystals, and some subordinate quartz.

PORPHYRITES. Nearest the plutonic types come certain large intrusions. The so-called syenites and diorites of Groby and Markfield in Leicester (57) are good examples. They consist of hornblende and felspar, both somewhat decomposed, the latter often exhibiting micrographic intergrowths with quartz, which are of interest

ANALYSES OF PORPHYRITES AND ANDESITES.

	Augite Porphy- rite, Tyne- mouth, Nor- thumb- land	Ensta- tite Porphy- rite, Pen- maen- mawr, Wales	Nephe- line Porphy- rite ("Pho- nolite"), Trap- rain Law	Augite Ande- site, Tuo- lumne Co., Cali- fornia	Ande- site, Silver Cliff, Colo- rado	Pyrox- ene Ande- site, Unga Island, Alaska
	(Stead).	(Phil- lips).	(Player).	(Stokes).	(Eakins).	(Hille- brand)
Silica ..	58.30	58.45	56.8	59.43	57.01	56.63
Titanium oxide	.75	n.d.	.5	1.38	.27	.67
Alumina ..	15.39	17.08	19.7	16.68	18.41	16.85
Ferric oxide .	4.50	.76	2.2	2.54	3.69	3.62
Ferrous oxide	4.76	4.61	3.5	3.48	2.36	3.44
Manganese oxide	n.d.	trace	.2	trace	.21	.23
Lime.. ..	10.96	7.60	2.2	4.09	4.29	7.53
Magnesia ..	2.68	5.15	.4	1.84	2.34	4.23
Potash ..	.94	1.02	7.1	5.04	3.72	2.24
Soda . . .	1.74	4.25	4.3	3.72	4.95	3.08
Water ..	—	1.07	2.5	.99	2.29	1.31
Etc. . . .	—	trace	—	85	.42	.35
	100.02	99.99	99.4	100.04	99.96	100.18

as the twin striations sometimes shew that the felspar is a plagioclase. Magnetite is an abundant accessory, while apatite also occurs and both epidote and chlorite appear as alteration products. The rock of Penmaenmawr in Wales (58½) is largely a typical pyroxene-porphyrity. Both enstatite and augite are present, the former being most common, though now largely represented by bastite pseudomorphs. The quartz and felspar shew almost as great a tendency to enter into graphic intergrowths as in

the Groby rock. Ilmenite is present in some quantity and sometimes builds skeleton crystals. Similar rocks are by no means uncommon as variations of large dolerite dykes. According to Maufe, small dykes of hornblende, augite, and enstatite-bearing porphyrite are extremely numerous around Ben Nevis in Scotland, where they constitute a "dyke-following" of the granite.

Hornblende-porphyrates are abundant in Eastern Australia, where they are often connected with gold-reefs. The handsome rock quarried as a building-stone at Bowral, New South Wales (57) is a hornblende porphyrite with conspicuous felspar phenocrysts. The well-known dyke of Wood's Point, Victoria, has brown hornblende occasionally edged with secondary greenish outgrowths of the same mineral, and some subordinate augite, which may be accompanied by a little biotite. Micropegmatite is abundant. Ilmenite and apatite are the accessories. Somewhat similar rocks occur as intrusive sheets among the Witwatersrand beds of the Transvaal, but the quartz seldom enters into micrographic intergrowths. An interesting variant occurs at Wonderfontein: the dominant ferro-magnesian constituent is a deeply coloured but very slightly pleochroic soda-augite, occasionally bordered by aegirine. There is also a very strongly pleochroic biotite. Large orthoclase crystals give the rock a porphyritic aspect in hand specimens, while the plagioclase builds smaller lath-shaped crystals. Interesting porphyrites occur at Brome Mountain (55½) and Mount Yamaska (57½), Quebec. These resemble the "Akerite" (58) of Christianity, Norway, which is composed of plagioclase, perthitic orthoclase, and augite, with subordinate quartz.

Many of the North of England dykes such as those of Eskdale, Armathwaite, Cleveland, Acklington, and Tyne-mouth are porphyrites with a silica percentage of 57 or 58. They have been described by Teall, and are all augite-plagioclase-magnetite rocks with a little interstitial glassy matter, bearing a close resemblance to the less basic and finer grained of the dolerites. Some of the rocks termed phonolites belong to this group. Among them should probably be included the well-known type from the Wolf Rock (56½) and that of Traprain Law, Scotland (57). Another is recorded by Card from Dubbo, N.S.W. (59½).

ANDESITES. These rocks take their name from their extensive development among the Recent lavas of the Andes. They are also common in New Zealand. Usually they shew abundant phenocrysts, but a vesicular type from Waimangu is made up of glass set with little felspar laths and augite granules, and has no porphyritic constituents.

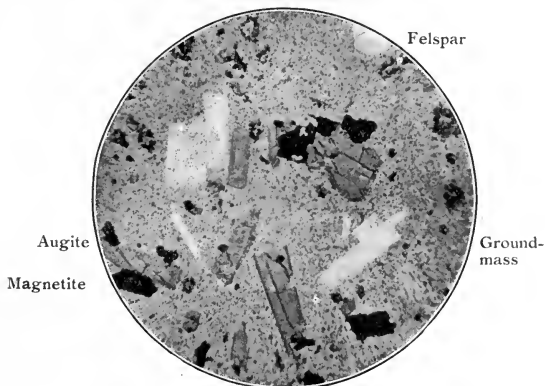


FIG. 74.—AUGITE ANDESITE. Himmerich, Nassau.
× 30 diam.

Andesites figure largely among the Tertiary lavas of Europe. A very fresh example from Himmerich, Nassau, shews porphyritic andesine and pale greenish yellow zoned augites in a groundmass consisting chiefly of felted felspar laths speckled with magnetite (see figure). Occasional flakes of biotite occur, shewing resorption effects.

In England, the Ordovician lavas and tuffs of the Lake District include many pyroxene andesites. Some are remarkable for the presence of little red garnets, and Harker, who has described many of them, has recently recorded abundant cordierite in a rock from Sty Head Pass. Many Ordovician andesites are also known in Wales, while others occur in Ireland. The Silurian lavas of Gloucestershire and Somerset, described by Professor Reynolds, provide some interesting examples of pyroxene andesites. Some are even-grained and resemble the

basalts. Others are more typical members of the group, shewing both augite and enstatite phenocrysts, the latter represented by bastite pseudomorphs, together with occasional porphyritic feldspars in a groundmass of feldspar laths and magnetite, with chlorite, calcite, and epidote as alteration products. The Old Red Sandstone lavas of the Cheviots and of the South-West Highlands, as well as of the Midland Valley of Scotland, include numerous flows of andesite. Interbedded with the Carboniferous rocks there are also andesitic lavas both in Northumberland and at a number of Scottish localities and in Limerick, Ireland.

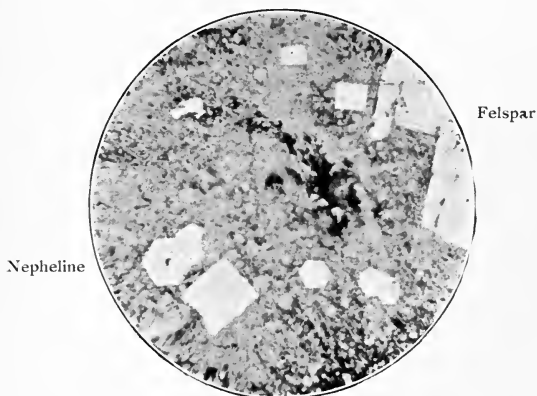


FIG. 75.—NEPHELINE ANDESITE. ("Phonolite.")
× 30 diam.

The lavas termed phonolites are felspathoid-bearing andesites for the most part. Nepheline is their most characteristic constituent, but hainyene and nosean often accompany it. Good examples from German localities are well known. Professor Marshall has recently described phonolitic lavas from a number of localities near Dunedin, New Zealand. Though common in Northern Africa and in the Equatorial region, none are as yet known from any part of South Africa.

CHAPTER XII.

The Basic Igneous Rocks.

THE basic rocks form a very diversified and interesting group. Not only are most of them holocrystalline, so that even among the lavas their composition is fully revealed by the microscope, but their structure is exceedingly varied, and even the few glassy types are remarkable for the incipient forms of crystallisation which they exhibit.

Augite and the basic feldspar *labradorite* are the most abundant minerals of the group, but *olivine* is often present in quantity, and is important as being practically confined to these and the ultra-basic rocks. Quartz is, of course, typically absent, and so are orthoclase, microcline and albite. *Enstatite* is of more importance among the coarse-grained types than in the lavas. It is not usually seen in olivine-bearing rocks which contain feldspar. *Hornblende* and *biotite* are rare, and are almost always deep brown when present. The bulk of the rocks containing the so-called feldspathoid minerals belong to this division. Nearly all the *leucite*-bearing lavas are basalts, while some containing *nepheline* are members of the same group. *Analcime* occurs occasionally among these rocks under circumstances which have caused many writers to regard it as original. *Magnetite* and *ilmeneite* may be looked upon as essential constituents of the basic rocks, in connection with some of which large segregations (?) of these minerals may occur. The minor accessories do not assume a very prominent position as a rule. *Apatite* is the only one which is seen in the lavas and finer grained dykes, where it usually forms long needles. In the coarser types, the dark *melanite* garnet is occasionally found, but like zircon and sphene, is rare. Calcite, epidote, serpentine and pyrites are often found as alteration products.

GABBROS. What are conventionally regarded as the plutonic types of this group are the rocks termed gabbros. It is highly probable, however, that certain

pyroxene and hornblende granulites have a much better claim to be regarded as the deep-seated representatives of the basic eruptives, though for convenience we shall include them among the metamorphic group. True gabbros are of comparatively infrequent occurrence, though the name has often been applied to the coarser dyke rocks. It is here restricted to the coarsely crystalline types with a granitic structure and the normal order of crystallisation. These usually have a specific

ANALYSES OF GABBROS.

	Gabbro, Ensta- Harz Mts., Ger- many.	tite- Gabbro, Em- erald Mine, Quebec	Olivine Gabbro, Sliga- chan River, Skye	Fels- pathic- Gabbro ("Anor- thosite"), Monhe- gan Island, Maine U.S.A.	Alkali- Gabbro ("Essex- ite"), Salem Neck, Mass.	Olivine- Ortho- clase Gabbro ("Shon- kinitite"), Yogo Peak, Montana. (Hille- brand).
	(Judd).	(Ditt- rich).	(Pol- lard).	(Lord).	(Ditt- mar).	
Silica ..	49.6	49.32	46.39	45.78	47.94	48.98
Titanium oxide	—	.42	.26	—	.20	1.44
Alumina ..	16.2	13.33	26.34	30.39	17.44	12.29
Ferric oxide .	1.9	1.28	2.02	1.33	6.84	2.88
Ferrous oxide	12.3	7.76	3.15	1.22	6.51	5.77
Lime.. ..	9.3	11.73	15.29	16.66	7.47	9.65
Magnesia ..	5.4	11.13	4.82	2.14	2.02	9.19
Potash ..	.8	1.12	.20	.10	2.79	4.96
Soda . . .	1.9	2.12	1.63	1.66	5.63	2.22
Water, ..	—	.64	.58	.51	2.04	.82
Etc. ..	3.3	.95	.20	—	1.04	1.79
	100.7	99.82	100.88	99.79	99.92	99.99

gravity between 2.8 and 3.1. It is difficult to cite good examples among the English rocks, but many are well known from the Western Isles of Scotland. The prevalent types in Skye and Rum consist of labradorite and augite, with abundant olivine and accessory magnetite. The Arran gabbros, on the other hand, are free from olivine. As in England, so in other parts of the world normal gabbros seem of very restricted distribution. Thus in Australia despite the extraordinary development of

Tertiary basic lavas and dykes, there are scarcely any occurrences of gabbro, though examples are known from Carcoar, N.S.W.

What is probably the most remarkable known development of basic rocks of plutonic type, is the great intrusion about four miles wide which runs in a nearly straight line through the middle of Rhodesia for about 250 miles. In places it consists of normal gabbro free from olivine (*e.g.*, Sarui River, Selukwe, Posselt's Vlei, etc.), but containing more or less enstatite. Even more common are types made up of enstatite with little or no felspar (Umvukwe

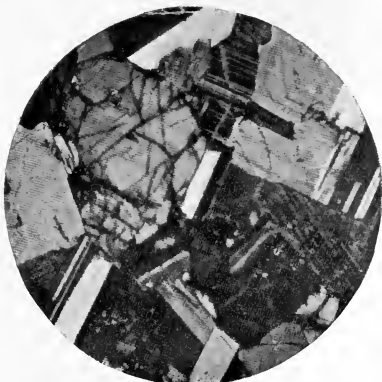


FIG. 76.—GABBRO, NEAR GWELO, RHODESIA.
+ nicols, \times 30 diam.

Hills, Doro Hills, etc.). These can scarcely be regarded as ultrabasic rocks, although they locally merge into types rich in olivine, as, judging from the analogy of analysed Transvaal "pyroxenites," they contain even more silica than the ordinary felspathic gabbros, *i.e.*, 54 or 55 per cent. These rocks are intimately associated with and sometimes pierced by ordinary dolerite dykes. Where serpentinised, as they sometimes are over considerable areas, they occasionally contain masses and veins of chromite (Makwiro and Selukwe) or magnetite (Makwiro and Indiva). These minerals, however, occur nowhere in the unaltered rock.

Other gabbros, wonderfully fresh, occur near Gwelo. They consist of diallagic augite and some faintly coloured pleochroic enstatite with a considerably larger amount of labradorite. There is no other mineral present.

Certain gabbros and dolerites which contain enstatite to the exclusion of augite, or at least in greater quantities, have been termed *norites*. Of this type is the rock enclosing the famous nickel deposits of Sudbury in Canada (50). As another we may mention the enstatite gabbro of Radauthal, Harz (49). It is not unlike the Gwelo rock

Felspar

Augite



FIG. 77.—OPHITIC DOLERITE. Near Kimberley Diamond Mine, South Africa. + nicols, $\times 15$ diam.

described above, but is not so fresh, rather finer grained, and the relative amount of augite is much smaller. There are some flakes of subordinate biotite, and occasional grains of magnetite. The felspar is anorthite with very fine twin striations. In some of the rocks belonging to this section of the gabbros, olivine occurs and may be abundant, but as a rule, in felspar-bearing rocks, olivine and enstatite do not occur together. Felspathoids seldom seem to occur in the strictly plutonic types of the basic division. Nepheline-bearing types have, however, been described from eastern Ontario by Professor Adams.

Even-grained rocks of thoroughly basic composition, but containing orthoclase, are known from several localities in the United States and Canada and have been termed *shonkinites*. These may contain a little nepheline. Certain Canadian gabbros shew conversion of their felspar into scapolite.

DOLERITES. The basic dyke rocks present every kind of diversity in mineral composition of which their chemical constitution admits. It is true that perhaps ninety per cent. have no special features of interest, but,

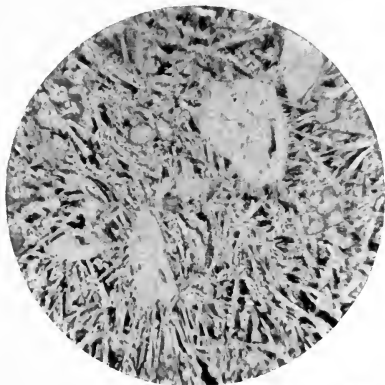


FIG. 78.—PORPHYRITIC DOLERITE, Umkondo Mine, Mashonaland, shewing enstatite phenocrysts in a ground mass of laths of augite and felspar.
× 40 diam.

on the other hand, no group includes members which differ so much from the mean, and their structures are as varied as their component minerals. There are three main types which are composed of plagioclase (usually labradorite) augite, and magnetite or ilmenite; one having a *granular* structure and differing little from the gabbros except in the finer grain and in the greater tendency to idiomorphism of the felspars; the second being *porphyritic*; and the third having an *ophitic* structure. These groups, of course, grade into each, and may be further subdivided. Thus what may be termed sub-ophitic types are common

in South Africa and Australia, while in other cases ophitic varieties become porphyritic owing to the development of large olivine crystals. Most dolerites are free from the last-named mineral, but in some it is abundant, and the chemical composition is no guide as to whether a rock may be expected to contain olivine in quantity, sparingly, or not at all. Its occurrence appears to be chiefly decided by the depth at which crystallisation commences and the temperature changes the rock undergoes before final consolidation. An ophitic structure evidently marks slow and undisturbed cooling under no very great pressure, while the granular structure marks more rapid cooling and movements during consolidation. Porphyritic crystals may occur in any type where crystallisation has begun at great depths, but olivine tends to be resorbed under sudden relief of pressure, while felspar phenocrysts are



FIG. 79.—SECTION ACROSS THE CLEE HILLS, SHROPSHIRE. Illustrating occurrence of the dolerite sills and the way in which they have preserved the Coal Measures from denudation. (After Murchison).

often due to the fact that the felspar obviously tends to separate out first under small pressures.

Any area will provide numerous examples of the types mentioned. Some intrusions are remarkably uniform, but a single mass will often exhibit all kinds of structures at different points. Among English rocks, the Rowley rag (49) is a good example of a granular dolerite containing some olivine; that of the Cleve Hills ($48\frac{1}{2}$) shews well-developed olivine crystals. The dolerite of Salisbury Crags, near Edinburgh, is interesting as containing analcime (*see* fig. 46); and the way this occurs in decomposition cavities is suggestive as regards some of the instances where the mineral has been considered original. This rock is very rich in apatite. Ophitic olivine-bearing types are well illustrated among those of the Derbyshire "toadstones," which are intrusive. Many Scottish and Irish intrusions are similar, and so are the Tertiary dykes of Eastern

Australia. This division is by no means so common in Africa, though there are numerous examples in the Karoo area of the Cape. The dolerite of Capetown ($52\frac{1}{2}$) is a good example of a normal granular augite-plagioclase-magnetite rock without any marked peculiarities, and many others might be cited as precisely similar.

Turning now to more exceptional types, we may first take an Australian example. This is a coarse-grained rock from Stringer's Creek, in Victoria, consisting of brownish hornblende and cloudy felspar in large plates; both of these, and especially the felspar, are crowded with small



FIG. 80.—COARSE GRANULAR DOLERITE. Scawt Hill, Co. Antrim, Ireland, $\times 15$ diam. (From *Geological Magazine*, after Gough).

augite crystals disposed in poecilitic fashion. An interesting rock is that of Kentallen, in Scotland (52), described by Messrs. Hill and Kynaston. Though an olivine-bearing type, it contains orthoclase. Another remarkable Scottish type is that of Loch Borolan (48), which consists of large and small orthoclase grains, melanite granules, also varying greatly in size, small biotite flakes and various alteration products, with one of which the orthoclase enters into micrographic intergrowths. To the eye the rock has a porphyritic aspect, though under the microscope the structure is a perfect muddle. Teall considers some of

the aggregates of orthoclase, etc., to represent leucite, and the observations of Lacroix on the 1906 eruption of Vesuvius shew the possibility of such a replacement. The leucite of certain ejected blocks was there found to be pseudomorphed by sanidine, often accompanied by sodalite, etc. Shand, however, after careful study on the spot has shewn that the pseudoleucite theory rests on a very slender basis. The Borolan rock is associated with other types containing nepheline, which is, however, sparingly developed. Nepheline and analcime bearing dolerites



FIG. 81.—FINE GRAINED DOLERITE. Shewing Skeleton Felspars (labradorite), Tati, Bechuana-land. $\times 30$ diam.

have recently been described from a number of Scottish localities, mostly occurring as intrusions of late Carboniferous or post-Carboniferous age.

A rock occurring at Ralentin, Bohemia, contains large augite phenocrysts, and leucite crystals or aggregates altered to analcime, which is perfectly isotropic. There are also occasional porphyritic feldspars and numerous grains of magnetite. The groundmass has very little effect on polarised light. Many of the rocks commonly termed "nepheline-syenites" should rather be grouped as nepheline-bearing dolerites. A good example has been described

by Wulff from Zwartkopjes in the Transvaal (53½). It is composed of pleochroic alkali-augite, with some aegirine and a little brown hornblende, together with nepheline, soda-orthoclase, a little plagioclase and some sodalite. Sphene, apatite, and magnetite are the accessories. Another rock of this class has been described by Card from Mt. Kosciusko (N.S.W.) in Australia (52½). It consists almost entirely of nepheline and aegirine.

ANALYSES OF DOLERITES.

	Normal Dole- rite, Whin Sill	Olivine Dole- rite, Cruik- ston, Gipps- land, Aus- tralia	Dole- rite, with Micro- pegma- tite, Kilsyth, Scot- land	Olivine Dole- rite, with Ortho- clase, Ken- tallen, Scot- land (Pol- lard).	Nephe- line Dole- rite, Zwart- koppies, Trans- vaal (Wul- ffing).	Leucite Dole- rite, Bear- paw Mts., Mon- tana, U.S. (Stokes).
	(Teall).	(Den- nant).	(Mac- donald).			
Silica ..	51.22	47.56	49.80	52.09	53.73	46.51
Titanium oxide	2.42	n.d.	1.56	.73	.09	.83
Alumina ..	14.06	16.79	17.77	11.93	20.35	11.86
Ferric oxide .	4.32	3.05	2.29	1.84	3.74	7.59
Ferrous oxide	8.73	8.71	8.75	7.11	2.13	4.39
Manganese oxide	.16	Trace	Trace	.15	.51	.22
Lime.. ..	8.33	8.57	8.85	7.84	2.72	7.41
Magnesia ..	4.42	6.30	5.67	12.84	.47	4.73
Potash ..	1.25	1.78	.48	3.01	6.05	8.71
Soda . . .	2.55	4.96	1.48	2.04	7.94	2.39
Water. . .	1.28	2.23	3.66	.35	2.02	3.55
Phosphoric acid, etc. . . .	.93	Traces	Traces	.67	.23	1.59
	99.67	99.95	100.31	100.24	99.98	99.78

Before passing on, it may be noted that the ancient hornblende rocks often called *epidiorites* are metamorphosed representatives of the basic igneous group, especially of the commoner intrusive types. The ophitic and other structures (porphyritic, poecilitic, etc.) seen in these rocks are often preserved in spite of recrystallisation and the paramorphic change of pyroxenes into amphiboles.

BASALTS. The basic lavas present a series of types as varied as the dolerites. Glassy varieties are uncommon, and even a vitreous groundmass or the presence of more than a very small amount of residual glass is unusual. Nearly all the basalts have a granular structure, though some are porphyritic, and the interior of a large flow which has cooled slowly may be more or less ophitic. Many of the active volcanoes of the present day and most of the areas of volcanic activity during the Tertiary period afford numerous examples of basaltic types. As a largely



FIG. 82.—AEGIRINE-NEPHELINE-DOLERITE,
Mt. Kosciusko, N.S.W., Australia.
× 20 diam.

glassy lava may be mentioned the 1881 flow of Kilauea, Hawaii. It shews scattered phenocrysts of olivine, augite and labradorite. A typical lava from Etna (50) shews a finely granular groundmass of augite grains, felspar laths, and magnetite, in which are embedded numerous porphyritic felspars, crowded with glass inclusions often zonally distributed. There are also phenocrysts of rather rounded olivine, and pale brownish augite. The Etna lavas represent among recent rocks the main types seen in the British Carboniferous, the South African Mesozoic, and the Australian Tertiary flows.

A beautiful porphyritic type of lava is that of the Lion's Haunch, Arthur's Seat, Edinburgh. The rock varies greatly from point to point, but the best-known type has sharply defined phenocrysts of pale brownish augite, olivine partly altered to serpentine, and felspar zoned with glass inclusions, in a fine groundmass shewing sharply bounded felspars, magnetite, augite, and some ill-defined residuum.

The Drakensberg lavas of South Africa are mainly olivine-bearing basalts. Those of the Victoria Falls

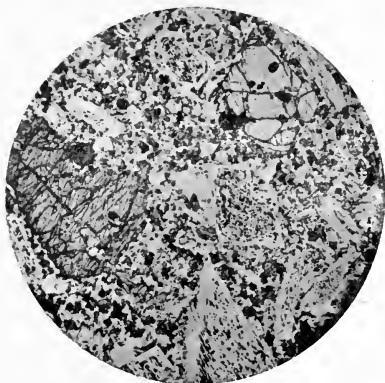


FIG. 83.—RECENT OLIVINE BASALT, shewing porphyritic olivine, augite, and felspar. Mt. Etna, Sicily. $\times 20$ diam.

region in Rhodesia (see fig. 84) on the other hand, do not contain olivine. They usually show felspar phenocrysts, grouped with a little augite in glomero-porphyritic aggregates sometimes very sharply defined from the finely granular augite-plagioclase-magnetite matrix.

Basaltic lavas containing orthoclase have been described by Cross from Colorado. An orthoclase-bearing basalt (51) is also recorded by Card from Berkeley, New South Wales. It contains $5\frac{1}{2}$ per cent. of potash and forms a transition to the leucite-bearing types. Most of the New South Wales Tertiary lavas are, however, normal olivine-

bearing basalts, like those of Orange, Carcoar, Cargo, Kiama, Tingha, New England, etc. That of Dapto (53) has no olivine, but shews conspicuous phenocrysts of labradorite together with less numerous augites in a microcrystalline groundmass.

Turning to the felspathoid-bearing basalts, we find leucite prominent, a fact which seems rather anomalous when we consider that in general the amount of potash in the igneous rocks decreases with the percentage of silica. Nepheline is rather rare. Melilite sometimes

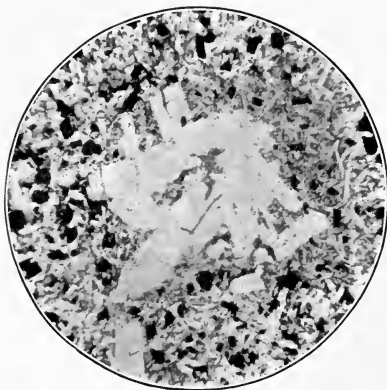


FIG. 84.—GRANULAR BASALT. With Glomero-Porphyritic Felspars, Victoria Falls. $\times 30$ diam.

occurs, but the rocks in which it is abundant mostly belong to the ultrabasic group. The sodalite family are present in a few exceptional instances. The ferromagnesian constituents are often alkali-bearing, and the augite is at times titaniferous, and exhibits a greyish-violet tinge. The hornblende is generally of the almost opaque brown "basaltic" type. Orthoclase occurs in some of these rocks.

The Vesuvian lavas are mostly leucite-basalts with about 46 to 47 per cent. of silica. They contain idiomorphic leucite in abundance, the characteristic anomalous double

refraction being well shewn, especially in those parts of the flows which have cooled most rapidly. There are also phenocrysts of olivine with opaque resorption borders,

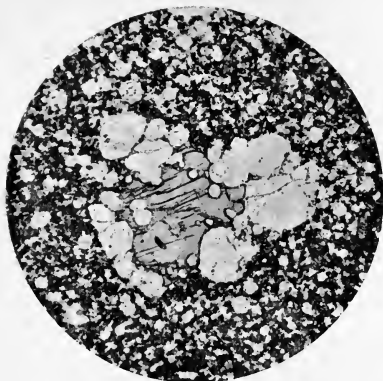


FIG. 85.—LEUCITE-BASALT.
Mt. Vesuvius, .
Italy.
× 20 diam.

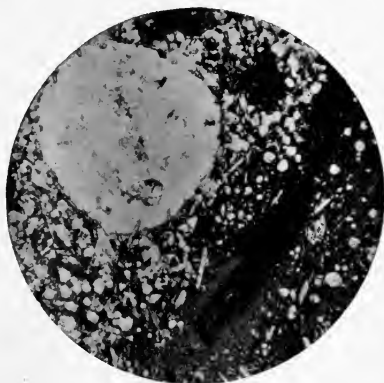


FIG. 86.—LEUCITE-BASALT.
El Capitan,
N.S.W.
× 50 diam.

pale green augite, plagioclase felspar, and occasionally orthoclase. The groundmass is sometimes made up largely of small felspar laths, and sometimes chiefly of small

leucites, with some partly vitreous residue, the former mineral being predominant, according to Johnston-Lavis, in the lavas of 1895—99 and the latter in those of 1906. The lava of the Capo di Bove, near Rome (46) contains tiny idiomorphic leucites, which are quite isotropic, and have numerous definitely arranged glass inclusions. In the groundmass augite and melilite play important parts, both occasionally forming large plates which envelop the leucite in poecilitic fashion. Olivine leucite basalts occur at Byerock, Harden and El Capitan in New South Wales.

ANALYSES OF BASALTS.

	Recent Olivine Basalt, Kilauea, Hawaii. (Merrill)	Olivine Basalt, Dry- noch, Skye (Pol- lard).	Olivine Basalt, Pap- anui, New Zealand (Mar- shall).	Ensta- tite Basalt, Eycott Hill, Cumber- land (Ward).	Leucite Basalt, Lava of 1881, Vesu- vius (Roth).	Nephe- line Basalt, Otago, New Zealand (Mar- shall).
Silica ..	48.71	46.61	45.39	51.10	48.59	49.39
Titanium oxide	1.81	1.81	n.d.	n.d.	n.d.	n.d.
Alumina ..	18.87	15.32	9.61	22.05	19.58	14.86
Ferric oxide .	3.18	3.49	9.27	1.21	4.38	7.35
Ferrous oxide	8.00	7.71	8.48	5.88	4.56	5.42
Manganese oxide	—	.13	n.d.	n.d.	n.d.	n.d.
Lime... ..	9.87	10.08	9.25	11.42	9.12	7.08
Magnesia ..	4.85	8.66	10.69	2.35	3.12	5.62
Potash ..	1.52	.67	.55	1.02	6.27	2.54
Soda . . .	4.15	2.43	3.14	2.22	2.15	4.71
Water. . .	—	3.17	2.81	.71	.12	2.52
Etc.	—	.08	—	2.00	2.04	—
	100.96	100.16	99.19	99.96	99.93	99.69

In the last biotite occurs abundantly, and encloses small crystals of both leucite and augite. At Rieden, Eifel, Germany (48), a rock occurs with large leucites, shewing the anomalous double refraction with wonderful distinctness, and accompanied by cloudy-looking nosean. There are no well-defined different generations, but the minerals mentioned, together with large orthoclase crystals (sanidine), smaller dark green augites, sphene and magnetite, are embedded in a fine matrix of nepheline and orthoclase with occasional granules of haüyne, apatite, melanite, etc.

The Carboniferous basaltic lavas of East Lothian, and those of apparently somewhat later date at Mauchline, in Ayrshire, are often alkaline in character, and occasionally contain nepheline.

Nepheline basalts (49) are recorded from Otago, New Zealand, by Professor Marshall.* He also describes an interesting lava containing both leucite and nepheline from Puketeraki, near Dunedin, in that district (53). The coloured mineral is pale green ægirine-augite, and there are abundant phenocrysts of anorthoclase. Another lava from the same district (52) contains both nepheline and sodalite, with aegirine and cossyrite as coloured constituents, and porphyritic olivine.

* *Q. J. G. S.*, vol. xiii, p. 409, etc.

CHAPTER XIII.

The Ultrabasic Igneous Rocks.

THOUGH far from abundant, the ultrabasic rocks are of wide distribution, and few regions are without a number of examples. They are typically very poor in silica and often in the alkalies, while rich in magnesia, and almost constantly containing small but notable amounts of such of the less common elements as manganese, cobalt, and especially chromium and nickel. As regards even rarer substances, it may be mentioned that they appear to be the original source of both the diamond and the precious metals of the platinum group. In spite of their small geological importance, an extraordinary variety of names has been invented for them, which it is not proposed to notice here.

The characteristic minerals of the division will be inferred from what has been said as to the chemical composition of the rocks themselves. All minerals rich in silica are naturally absent, and even the *felspars* are often missing, or only present in small proportion. It may be noted, however, that a number of felspar-free rocks, notably certain "pyroxenites," contain considerably more silica than the types properly included in this group; while, on the other hand, the presence of anorthite in large amounts is quite in keeping with the low silica content of this division. Where the alkalies are relatively abundant, they may give rise to *nepheline* or *leucite*, and where lime is predominant rather than magnesia, *melilite* is often seen. Some of the deeper-seated members of the group are almost pure olivine rocks, or olivine-chromite rocks, and *olivine* is nearly always an important constituent, whatever other minerals may occur, even entering in a second generation into the composition of the ground-masses of the dykes and lavas. *Augite*, *enstatite*, brown *hornblende*, and *biotite* are sometimes abundant in the coarser types, but the last three are seldom present in the

finer-grained and porphyritic varieties. Many leucite- and nepheline-bearing rocks are properly included in this division, and *melilite* is frequently present in the most basic section of it. This mineral may enclose the other constituents in poecilitic fashion, but usually forms little laths, striated parallel to the base, which is, however, the direction of elongation. They do not shew such sharp boundaries as feldspar, for which they may nevertheless be mistaken in the absence of the characteristic "peg structure," which, by the way, is not particularly common. Augite is a frequent constituent of the groundmass in porphyritic types, but in fresh rocks care must be taken not to mistake olivine for this mineral. *Magnetite* and *ilmenite* are often present in abundance, while *perovskite*, *picotite* (chrome-spinel) and *chromite* are accessories which specially characterise this group, and are very rarely met with outside it. *Garnet* is sometimes abundant, usually pyrope or melanite.

PICRITES. It is questionable, in spite of certain theories which account for the more basic rocks as derived from far greater depths than the acid types, whether any of this group ought strictly to be classed as plutonic at all. They never occur in masses of any great size, and since quite small dykes may be coarsely crystalline and of thoroughly granitic structure, these last points cannot be taken as evidence of a plutonic origin. We shall therefore group all the intrusions together as picrites. Owing to the readily attacked nature of the minerals they contain, all the members of this group, even of late geological date, are frequently far from fresh, serpentine being a characteristic alteration product, and sometimes replacing the whole bulk of the rock.

The picrites are well illustrated among British and Colonial rocks. The well-known example from Dun Mountain, New Zealand (43), is a coarse-textured aggregate of irregular, much-cracked grains of olivine, with some chromite; indeed, it grades into a pure chrome-iron ore, and, on the other hand, into gabbro-like types. In the Transvaal and Rhodesia occur rocks of closely similar appearance. These are, however, as a rule, pyroxene rocks ("pyroxenites"), often belonging really to the basic as opposed to the ultrabasic group. Olivine is

nevertheless locally abundant. A Rhodesian rock from the Ingezi River, on the coach road between Selukwe and Victoria, is an admirable example of the less basic picrites. It consists chiefly of olivine and enstatite, both showing serpentine along cracks, and the former mineral separation of magnetite in addition. There is also a little augite and light brown hornblende, as well as some quite subordinate feldspar. Another and well-known rock of this class is that described by Judd from Loch Scye in Scotland (42). It shews large plates of colourless hornblende and nearly colourless biotite enclosing greenish granules of serpentinised olivine and grains of magnetite and apatite.

A rock from Barnton, Edinburgh, shews partly serpentinised olivine, deep brown biotite, and pinkish augite, with occasional feldspars evidencing an ophitic tendency. Magnetite and apatite are the accessories. Another type from Radauthal, Harz, Germany (42), shews olivine and enstatite, the former, as usual, partly converted into serpentine, with occasional feldspars, which again exclude the rock from the plutonic division by shewing its tendency to assume an ophitic structure. Augite bearing picrites are represented at Gundagai, N.S.W. At Ballarat and Maldon (Vic.) numerous fine-grained picrite dykes of Tertiary age intersect the Ordovician strata.

From Skye and Rum, in Scotland, Harker has described under the name of "Allivalite" interesting ultrabasic intrusions (42) containing much feldspar (anorthite) together with olivine and with or without subordinate augite.

The "ijolite" of Alnö, Sweden, illustrates the section rich in alkalis. It consists of nepheline, speckled with the alteration product cancrinite, green soda-augite and dark melanite garnet, with apatite and sphene as accessories and secondary calcite and pyrites. A rock related to this is the so-called "jacupirangite," composed of alkali-augite and bluish green hornblende, with a large amount of magnetite and apatite and a little secondary calcite. The relationship of rocks like these to such types as the augite syenites and diorites described from the neighbourhood of Bulawayo is obvious, the ferro-magnesian minerals being strikingly similar. It may, indeed, be remarked that some of the basic patches, resulting from the absorption of masses of hornblende schist into those

rocks, are identical in nearly every way with the jacupirangite of Alnö.

Several highly alkaline types of picrite have been described by Professor Adams from Monmouth, Ontario-Canada. One (43½) consists of nepheline, albite and hornblende, with a little primary (xenolithic) calcite and accessory apatite. Another (42½) has nepheline making up about half the rock, abundant deep green augite, albite, some calcite, a little garnet sometimes bordering the augite, and as accessories magnetite and apatite. A third type, which has been termed "Monmouthite" (39½) consists essentially of nepheline and green hornblende. Subordi-

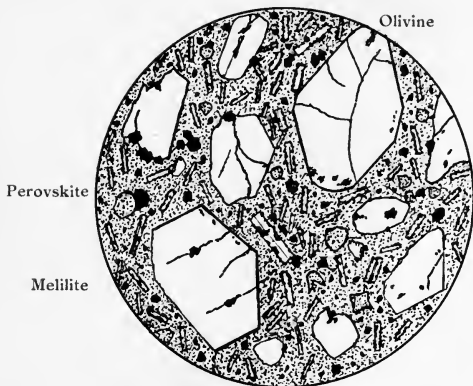


FIG. 87.—OLIVINE MELILITE PICRITE. Spiegel River, Cape Colony. $\times 40$ diam.

nate cancrinite and calcite also occur together with very small amounts of sodalite, biotite, apatite, sphene, and iron ores.

Professor Reynolds describes from Bartestree, near Hereford, England, an interesting rock (43) which may be referred to here. It consists of serpentinised olivine, often in crystals of considerable size, which makes up in some cases fully one-third of the rock, together with fresh augite, some labradorite, and analcime; magnetite and apatite being accessories. This rock is associated with

less basic and finer grained types (dolerite) which go to form a composite dyke intrusive in Old Red Sandstone strata. Another rock of this class, which has been termed "teschenite," is that occurring as small dykes at Bondi, near Sydney, New South Wales ($43\frac{1}{2}$). This has abundant porphyritic olivine, and augite, with some felspar and patches of analcime in a partly vitreous groundmass containing much magnetite.

A beautifully fresh and very interesting representative of the most basic picrites occurs at Spiegel River, in Cape Colony (36). It consists of sharply defined olivine

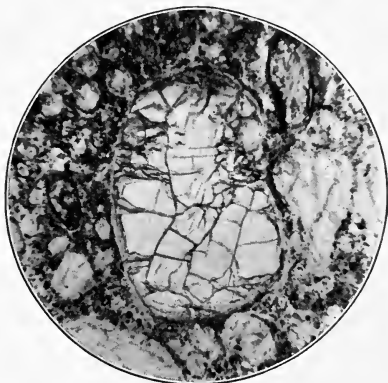


FIG. 88.—"BLUEGROUND" Kimberley Diamond Mine, Cape Colony. $\times 20$ diam.

crystals, embedded in a groundmass showing some augite, indications of a second generation of olivine, laths of melilite, and granules of perovskite, which, in spite of their deep clove-brown colour, shew well the anomalous double refraction under fairly high powers. Weathered portions of the rock at once suggest its close relation to the much altered fillings of the Kimberley and other diamond "pipes." The "Kimberlite," or "blue-ground" of these famous diamond mines, has given rise to much controversy, both with regard to its own origin and that

of the diamonds it encloses,* but it is best referred to here. Where out of reach of surface alteration, hand specimens are of a greenish or bluish colour, and shew scattered pyrope garnets, ilmenite, augite (chrome-diopside), and olivine in grains about the size of a pea, as well as flakes of mica and numerous rock fragments torn off the walls of the vent, or which have subsided into it from above. Under the microscope, the matrix is seen to have been altered into a calcite-bearing serpentine, speckled with perovskite, magnetite, etc., and containing phenocrysts of olivine, augite, pale-brown mica, garnet, and ilmenite, with rarer hornblende and occasionally enstatite. In the hardest and freshest variety of the rock (which is perfectly black) at the De Beers Mine, Kimberley, are to be seen little laths of calcite, which are no doubt pseudomorphs after melilite. The mica of the "blue ground" sometimes shews reverse pleochroism, as does that of the granite forming the wall of the De Beers pipe at a depth of over 2000 feet. A deeper tint is shewn when the cleavage is normal to the shorter diagonal of the lower nicol than when it is parallel. The diamond-bearing rocks of the Orange River Colony, the Transvaal and Rhodesia are all similar to those of the Kimberley area, and occur in the same way, namely, filling volcanic "pipes," or "fissures." Numerous volcanic vents, filled wholly or in part with fresher rocks which are not diamantiferous, have been described during the last few years by the Cape Geological Survey. These often contain melilite. Rocks precisely similar to those of Kimberley, and shewing the same abundance of inclusions, occur as well defined dykes at Syracuse, New York, and have also been shewn to contain melilite.

A European rock which may be referred to here is that of Alnö, Sweden, which has been termed Alnöite. It shews large phenocrysts of light-coloured biotite, with others of augite, and serpentinised olivine, embedded in a somewhat altered groundmass, in which may be made out small flakes of biotite, laths of melilite, and grains of ilmenite. An allied type with the melilite in large plates

* See *Genesis and Matrix of the Diamond*, by Prof. H. Carvill Lewis, and several papers by Prof. Bonney in the *Geol. Mag.* and elsewhere; also Dutoit, *Rep. Cape Geol. Comm. for 1906* (1907).

has been described by Flett from the Orkney Islands (35½). Other rocks of extremely basic composition occur as small dykes in the neighbourhood.

LIMBURGITES. The ultrabasic lavas are generally known as limburgites, from the well-known rock of the Kaiserstuhl, in Baden, at Limburg (43). This shews large, well-defined crystals of purplish augite, and smaller ones of partly altered olivine, in a groundmass of augite and

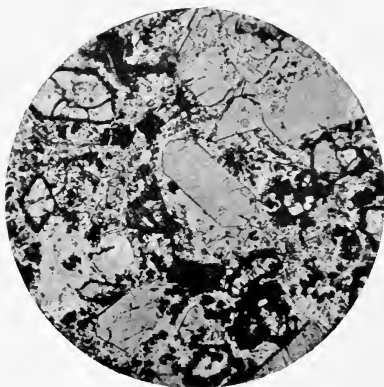


FIG. 89.—LIMBURGITE, Kaiserstuhl,
Baden. $\times 20$ diam.

magnetite granules with some residual glass. A very similar rock from the Zoutpansberg, in the Transvaal, shews phenocrysts of olivine and augite in a glassy groundmass covered with rods and fern-like skeletons of magnetite. Both this rock and the last, in their coarser modifications, have a tendency to the development of fine needles of felspar in the groundmass. In that from the Transvaal these are shewn by their high extinction angles to be closely allied to anorthite. In a rock of this type from among the recent lavas of Ruwenzori, in Central Africa, the augite phenocrysts are larger than those of olivine, and are of a faintly brownish colour. Large irregular magnetite grains also occur. The groundmass consists

of a second generation of augite, with magnetite and a little glass. Certain lavas which differ very little from ordinary basalts save in containing small patches of analcime must be included in this group. An excellent example is the Tertiary lava of Bathurst, New South Wales (44). This contains phenocrysts (sometimes composite) of olivine and augite. The complete freshness of the former supports the theory of a primary origin for the analcime.

ANALYSES OF ULTRA-BASIC ROCKS.

	A.	B.	C.
Silica	39.16	42.20	39.74
Titanium oxide .. ..	.11	.09	.13
Alumina	1.11	17.56	30.59
Chromic oxide .. ..	.61	.06	—
Ferric oxide	2.47	1.20	.44
Ferrous oxide	11.44	6.33	2.19
Manganese oxide .. ..	.15	.18	.03
(CoNi) O .. .. .	.15	.13	—
Copper oxide .. .. .	.06	.04	—
Lime .. .. .	.58	9.61	5.75
Magnesia	43.64	20.38	.60
Potash .. .. .	.16	.11	3.88
Soda .. .. .	.08	1.11	13.25
Sulphur .. .. .	.04	.02	.07
Chlorine	—	—	.02
Carbonic acid	—	—	2.17
Water .. .. .	.80	1.19	1.00
	<hr/> 100.56	<hr/> 100.21	<hr/> 99.86

A. "Peridotite" Allival, Isle of Rum (Pollard). Olivine, with a little Anorthite and Chromite. This illustrates a specially magnesia-rich example of the prevalent olivine-bearing types.

B. "Allivallite," same locality (Pollard). Olivine with about equal anorthite and a little augite and magnetite. An exceptionally felspathic type.

C. "Monmouthite," Ontario, Canada (Connor). Hornblende-Nepheline rock. This illustrates the extreme of the rather exceptional alkali-rich types.

Most of the so-called melilite basalts belong to this or the preceding group, of which, indeed, they constitute some of the most basic members. That of Hochbohl, in Wurtemberg, may be cited (34). It shews olivine and augite phenocrysts, in a crystalline groundmass of minute

melilite laths, with a little biotite and magnetite, and perovskite grains. Another example is described by Professor Marshall from among the interesting and diversified series of lavas near Dunedin, New Zealand. It has porphyritic olivine, much augite and some plagioclase, the melilite forming irregular patches containing inclusions of these minerals.

METEORITES. As an addendum to this section, we may mention the meteorites, of which the stony types closely resemble the terrestrial ultrabasic rocks. They consist, as a rule, of ferro-magnesian minerals, such as

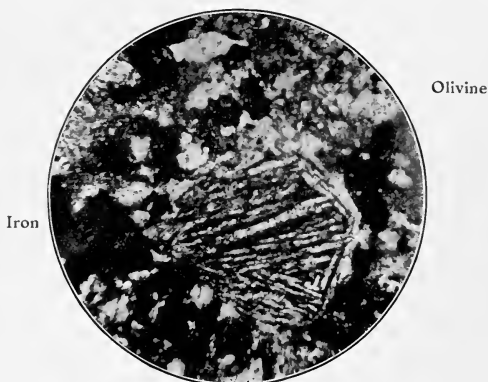


FIG. 90.—METEORITE. Shewing Chondritic Structure.
Pultusk, Poland. $\times 40$ diam.

olivine and enstatite, associated with some nickel iron, and frequently shew a special structure known as the *chondritic*, due to the occasional aggregation of the constituents in rounded grains made up of fibres radiating from a point on the circumference (see figure). It is worthy of note that though these remarkable bodies owe most of their interest to the fact that they have dropped from the sky, the most plausible theory of their origin would have us regard them as the products of ancient terrestrial volcanoes, which, after circling through space for an indefinite period, have fallen back again on the earth.

CHAPTER XIV.

The Sedimentary Rocks.

THE sedimentary rocks, having been directly or indirectly derived from those of igneous origin, may generally be expected to contain such constituents of the latter as are most abundant and resistant to weathering. They are, in fact, usually composed of such substances, quartz, on account of its hardness and unalterable nature, being especially conspicuous. But besides rocks of an obviously *clastic* or fragmental nature, there is the important group of the limestones, which contain, instead of mechanically derived fragments, substances which have been subjected to chemical changes, and after having been dissolved in water, have been thrown down again, in the majority of cases, by the action of living organisms. The tests, or hard parts, of these creatures are generally to be recognised in abundance among rocks of this class.

Fragmental Rocks.—The coarsest sediments of detrital origin contain many recognisable rock fragments in a more or less worn condition. These are usually embedded in a matrix consisting either of the same materials in a finer state of division, or of more readily decomposed substances; but in certain cases they have been cemented together by chemical precipitates, like carbonate of lime, silica, or iron oxides. When loose and incoherent, rocks of this group are termed *gravels*, or pebble beds. In a more compact state they are styled *breccias* when made up of angular fragments; and *conglomerates*, when their constituents are more rounded. When loose, the pebbles may be collected and studied in a similar way to the rocks from which they are derived. The finer materials of the matrix may be sorted out by sifting, and then treating them by a process of washing like that familiar to every prospector and miner for tin or gold. The heavier minerals will often be found to include many interesting species.*

* See, for instance, H. H. Thomas, *Q.J.G.S.*, Vol. lviii, 1902, pp. 620-631, and plates xxxi and xxxii.

The remains of organisms are also not infrequently present. When pebbles and matrix are held together in a compact mass owing to the infiltration of cementing materials, or to great pressure, slices may be made in the ordinary way, and the relations of pebbles, finer detritus and cement accurately made out.

Sands and *Sandstones* comprise those fragmental rocks in which the size of the individual grains is reduced to such an extent that each, as a rule, represents a single mineral, broken or worn down from the original rock in

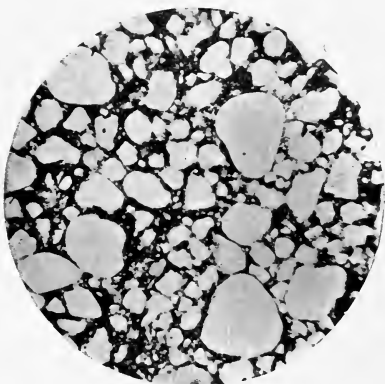


FIG. 91.—SANDSTONE, with windworn grains. Forest Vale, Rhodesia. $\times 30$ diam.

which it was formed. Quartz is much the most abundant constituent of sandstones, and makes up the great bulk of most occurrences. Impure, coarse sandstones are frequently termed *grits*, and those in the older formations, full of minute rock fragments were, at one time, universally called *greywackés*. Highly felspathic sandstones are sometimes known as *arkose*. Rounded glauconite grains, often casts of the chambers of foraminifera, give their characteristic colour to many “greensands.”

The individual sand-grains may be packed closely together, almost without cementing material, or the

cement may make up a large proportion of the rock. The former is the case with the English "Pennant sandstone," and of the latter good examples are found among the Purbeck beds. The shape of the grains varies from almost perfectly spherical to sharply angular. In most sandstones the larger grains are sub-angular, and the smaller ones quite sharp. Where currents have had much influence, as on shoals, the grains are usually well-rounded, but rounding is only seen in perfection among desert sands that have been continually shifted by the wind. Good examples are seen among the English Triassic sandstones. They are well represented among the presumably Jurassic Forest sandstones of Rhodesia. Even in these rocks the smallest grains are quite angular. Grains of perfectly fresh microcline and other feldspars constantly occur, as well as complete crystals and fragments of minerals like zircon and tourmaline.

Silica is perhaps the commonest cementing material, and may occur either in the form of quartz, or chalcedony, and even opal. The two latter cases are exceptional, but chalcedony occurs at times in the English greensands, and opal is the cement of some of the Forest sandstones just referred to. Hard quartz-cemented sandstones are specially characteristic of the older formations. In the tropics, however, masses of silicified sand or *surface-quartzite* are found even among the recent deposits, and the *sarsen-stones* of the English Tertiaries seem to be of a kindred nature. The secondary quartz of many sandstones takes the form of enlargements of the original grains, which show the same interference tints in polarised light, though the original boundaries can often be traced. Exceptionally these enlargements may develop good crystal outline, as in the case of the well-known Penrith sandstone of Cumberland. This is a very loose-textured rock, but a continuation of the process may cement it into a hard "quartzite," with some of the crystal faces still preserved in places, as in the Palæozoic sandstone of the Umkondo Mine, Mashonaland. Secondary enlargements of feldspar, hornblende, etc., have also been noticed at times, as pointed out by C. R. Van Hise.

Calcite is found cementing the grains in numerous instances. The New Red Sandstones of Britain are

interesting for the variety of binding materials they show. Calcite is common and dolomite is found in Somersetshire and elsewhere. Iron oxides are of frequent occurrence. Barytes has been recorded from near Nottingham and in Scotland, while fluor,* celestine, and gypsum are also known.

The argillaceous interstitial matter often seen, has sometimes been deposited as mud or clay among the sand grains. In other cases it is evidently due to the decomposition of original felspar granules which have afterwards been squeezed between the other particles, as may be observed in the English coal measures.

The heavy minerals of sands, like those of gravels, show many features of interest. Magnetite is much the most common as a rule, but ilmenite, rutile, tourmaline, staurolite, garnet and zircon are often to be found, together

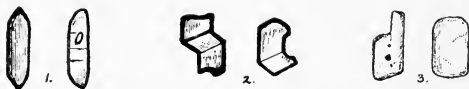


FIG. 92.—MINERALS ISOLATED FROM THE BAGSHOT SANDS.
1. Zircon. 2. Rutile (twin crystals). 3. Tourmaline.
× 100 diam.

with even rarer minerals. The English Bagshot beds contain good crystals of rutile and zircon, the former sometimes showing the characteristic geniculate twins. Kyanite, tourmaline, &c., may also be recognised. Heavy solutions are of great assistance in separating the various constituents from one another.

Clays and *shales* comprise two main types, between which every gradation may, however, be observed. At one extreme we have those composed almost entirely of minute angular quartz grains, and at the other, those consisting of argillaceous matter often largely resolved into micaceous and chloritic alteration products. Owing to their fineness, the discrimination of the constituents of rocks of this class is a matter of considerable difficulty, and they should be studied in sections reduced to the utmost possible thinness. The slates show similar features

* See Mackie, *Rep. British Assoc. for 1901*, pp. 649-650.

to the shales, but their grains have been rearranged roughly parallel to the direction of cleavage. Secondary quartz and pyrites are frequently observed as well as magnetite grains and rutile needles. Iron oxides are the usual colouring materials, but carbonaceous matter gives a blackish, and finely divided pyrites a greenish tinge in many cases.

The *laterite*, often termed surface ironstone, ferruginous

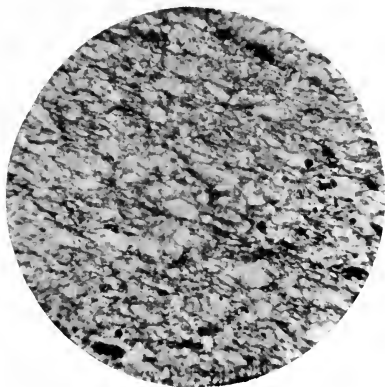


FIG. 93.—SLATE. Gympie, Queensland.
× 50 diam.

conglomerate or concretionary limonite, arising from the decomposition *in situ* of almost every class of rock under tropical conditions, is very common in India, Northern Australia, Central Africa, etc. These deposits are really of sub-surface origin in most cases, forming under the soil in places frequently saturated with moisture. In many occurrences they have been shown to have *bauxite* (aluminium hydrate), rather than hydrated iron oxide, as their chief constituent,* but the contention of certain writers that the term should be restricted to the highly

* See Holland, *Geol. Mag.*, 1903, pp. 59-69, and Warth, *ibid*, pp. 154-159; also Maclaren, *Geol. Mag.*, 1906, pp. 536-547; and Mennell, *Geol. Mag.*, 1909, pp. 350-2.

aluminous types can scarcely be admitted. There is no means of distinguishing in the field between the varieties rich in iron; and those richest in alumina, and the distinctive feature of the deposits as a class is the fact that they are made up largely of hydrated oxides instead of the hydrous silicates which characterise ordinary clays and earths. They often contain large amounts of detrital material, and in many instances the oxides do little more than cement together numerous fragments of vein quartz and other substances derived from the underlying rocks. Concretionary pisolitic structures are common.

The *limestones* are perhaps chiefly interesting to the geologist on account of their abundant organic remains. In some cases, as in the chalk and the Tertiary nummulitic rocks, they are largely composed of the tests of foraminifera; while crinoidal, shelly and coral limestones occur in many formations all over the world. By far the most important of the foraminifera is the open-sea or *pelagic* organism, *Globigerina bulloides*. As it lives floating on the surface, its remains are to be found in all classes of deposit, but where land-derived materials are abundant (*terrigenous deposits*) it is inconspicuous among the mass of sediment. In the deep sea, or *oceanic deposits*, however, it becomes very prominent, and the *Globigerina ooze*, found covering the sea bottom at great depths, is largely made up of its remains. The chalk is an older deposit of precisely similar character, in which the small amount of siliceous material has segregated together to form bands or nodules of flint. It contains the same or a closely allied species of globigerina, and also the minute structures known as *Rhabdoliths* and *Coccoliths*, supposed to have been detached from calcareous algæ, of which the former, when highly magnified, are like tiny hammers, and the latter much resemble collar studs.* Besides the recognisable organisms, concretionary or *oolitic* structures are often observed among the calcareous rocks, which appear to be due in many instances to the action of minute algæ. A fossil creature, possibly of this nature, has been named *Girvanella*, and is seen in many rocks. Recrystallisation

* See figures in Judd's *Student's Lyell*, p. 50.

of the calcitic matrix is frequently seen, also the replacement of calcite by dolomite, which appears to take place extensively on modern coral reefs. An interesting summary of the features of the British limestones is given by Harker and should be consulted by the English student.* Concretionary *surface limestones* or calcareous tufas are of common occurrence in tropical regions, just as are the

ANALYSES OF SEDIMENTARY ROCKS.

	Composite of 253 Sand- stones	Composite of 51 Palæo- zoic Shales	Composite of 27 Meso- zoic and Cainozoic Shales	Composite of 345 Lime stones
	(H. N. Stokes).	(H. N. Stokes).	(H. N. Stokes).	(H. N. Stokes).
Silica	78.66	60.15	55.43	5.19
Titanium oxide..	.25	.76	.46	.06
Alumina.. ..	4.78	16.45	13.84	.81
Ferric oxide ..	1.08	4.04	4.00	.54
Ferrous oxide ..	.30	2.90	1.74	—
Manganese oxide.	trace	trace	trace	.05
Lime	5.52	1.41	5.96	42.61
Strontia	trace	—	—	—
Baryta .. ..	.05	.04	.06	—
Magnesia . . .	1.17	2.32	2.67	7.90
Potash	1.32	3.60	2.67	.33
Soda .. ..	.45	1.01	1.80	.05
Lithia	trace	trace	trace	trace
Water	1.64	4.71	5.56	.77
Phosphoric acid .	.08	.15	.20	.04
Carbonic acid ..	5.04	1.46	4.46	41.58
Sulphurous acid .	.07	.58	.78	S. 14
		C. .88	.69	Cl. .02
	<hr/> 100.41	<hr/> 100.46	<hr/> 100.48	<hr/> 100.09

laterites, and appear to be derived by very similar leaching processes from rocks rich in lime silicates.

Chert and flint appear to be occasionally original, but are more probably due, in most cases, to the replacement

* *Petrology*, pp. 256-270 of 3rd Edition.

of limestone shortly after its original deposition. When original, they consist almost exclusively of sponge spicules, radiolaria and other siliceous organisms. Generally, however, they show the replacement of shells, foraminifera, and even of oolitic structures, evidencing their secondary nature. Deposits of radiolarian ooze occur in the oceans usually at greater depths than the foraminiferal deposits, but not so deep as the abysmal red clays, which result from the decomposition of floating pumice and volcanic

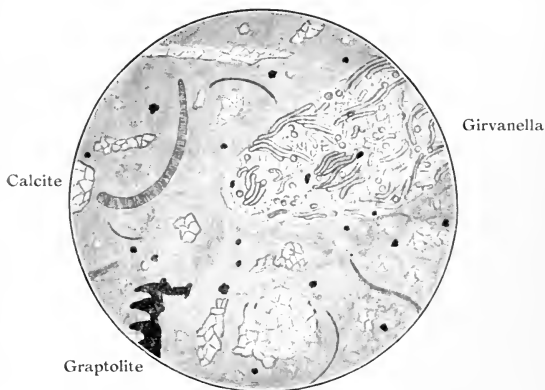


FIG. 94.—STINCHAR LIMESTONE (ORDOVICIAN), showing *Girvanella*, part of a graptolite, shell fragments, &c., also re-crystallised patches. Benane Burn, near Girvan, Ayrshire, Scotland. $\times 30$ diam.

ash which has scattered far from its original source. Tertiary radiolarian deposits, no doubt of deep sea origin, occur in the Barbados, and compacted *radiolarian cherts* are found in many of the older formations, as the Carboniferous of Devonshire, the Devonian of New South Wales, and the Ordovician of the south of Scotland. In the *diatomaceous earth*, for which a number of industrial uses have been found, we have a lacustrine deposit due to the accumulation of the siliceous skeletons of the lowly vegetable organisms known as diatoms. They occur in rivers, but seldom make important deposits, though

the ordinary bath-brick of commerce, derived from the river Parret, contains their remains. Marine diatoms contribute to the formation of some oceanic oozes and cherty rocks. Hot springs often give rise to deposits of *siliceous sinter*, which is at first of an opaline character, but is found changed into chalcedony or quartz around many extinct sources. The *silicified wood* embedded in various strata of terrestrial and fresh water origin often shows very perfectly preserved cells and tissues.

Coal may be mentioned here. It generally consists of compressed stems, roots, and leaves of various types of

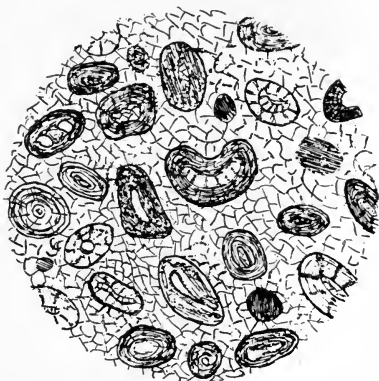


FIG. 95.—OOLITIC LIMESTONE, near Bath, England.
× 20 diam.

plants, and seldom shows much in the way of definite structure under the microscope. Sometimes, however, spores, etc., are seen in abundance.

Appendix: Tuffs, etc. Sediments of all descriptions and all ages at times contain volcanic materials mixed with their more normal constituents. Near centres of eruption these may become very abundant, and the deposits may grade into true *tuffs*, or beds of volcanic ash. Even coarser material may occur in masses or beds, but as far as former geological periods are concerned, such *agglomerates* generally fill old volcanic vents or pipes.

COMPLETE ANALYSES OF RECENT MARINE SEDIMENTS.*

	Composite of 51 Samples of Oceanic "Red Clay" (Steiger).	Composite of 52 Terri- genous Clays and Muds (Steiger).
Silica	54.48	57.09
Titanium oxide .. .. .	.98	1.27
Alumina	15.94	17.24
Chromic oxide .. .. .	.012	.05
Ferric oxide	8.66	5.07
Ferrous oxide .. .. .	.84	2.30
Nickel and cobalt oxides .. .. .	.039	undet.
Manganese oxide (MnO)	—	.12
Manganese peroxide (MnO ²)	1.21	—
Magnesia	3.31	2.17
Lime	1.96	2.04
Strontia .. .. .	.056	.03
Baryta .. .. .	.20	.06
Potash	2.85	2.25
Soda	2.05	1.05
Vanadium oxide .. .. .	.035	.03
Arsenious oxide .. .. .	.001	undet.
Molybdic oxide	trace	—
Phosphoric acid .. .. .	.30	.21
Sulphur	—	.13
Copper oxide .. .. .	.024	.02
Lead oxide .. .. .	.008	undet.
Zinc oxide .. .. .	.005	undet.
Carbon	—	1.69
Water (combined)	7.04	7.18
	100.00	100.00

(The above analyses from Clarke's *Data of Geo-Chemistry* have been made strictly comparable by the rejection of sea salts, calcium carbonate and hygroscopic water, and recalculation to 100 per cent.)

* These analyses are particularly noteworthy as affording proofs of the primary presence of some of the ordinary commercial metals among perfectly unaltered sediments in a much more convincing manner than has been done for any igneous rocks.

The fine ashy material of tuffs may consist almost entirely of minute glass fragments (*pumiceous tuffs*, etc.). In the case of acid rocks, these retain well their sharp edges, and are easily identified even among the older formations. Basic glasses, however, are more readily altered, and by hydration give rise to the so-called *pala-gonite tuffs*. Some ashes contain little glass, and consist almost entirely of crystals and crystal fragments, as in the case of the West Indian eruptions of 1902. When

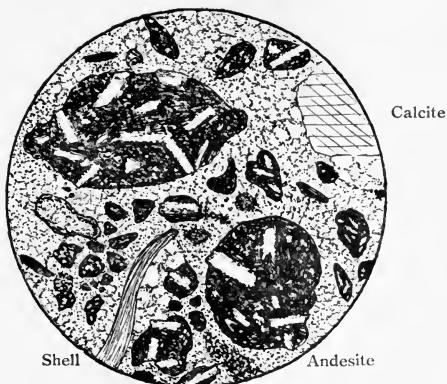


FIG. 96.—CALCAREOUS ANDESITIC TUFF, Charfield, Gloucestershire, England. $\times 30$ diam.

consolidated these would form *crystal-tuffs*. Rounded lava fragments known as *lapilli* are often found, and give a clue to the nature of the flows connected with the explosive outbursts. Tuffs and agglomerates often contain much material torn off from the rocks alongside the volcanic neck; indeed some pipes are almost entirely filled with such extraneous materials, *e.g.*, in the Auvergne region, as well as many of those recently discovered in the Sutherland district of the Cape by the Cape Geological Survey.

Where the volcanic materials have fallen upon a sea or lake bottom, they may entomb numerous organisms: in fact the great destruction thus caused sometimes gives

rise to richly fossiliferous deposits. Where, as in the example figured, the ashes are much intermixed with organic remains and matter of sedimentary origin, this is generally to be accounted for, no doubt, by redistribution due to the action of the waves. Infiltration of cementing materials is observed just as in the case of mechanical sediments: indeed it is sometimes difficult, among the older formations, to distinguish from true tuffs the sediments derived from the denudation of volcanic rocks. An excellent example of such a type of sediment is the "grit" associated with the Kirkland conglomerate (Ordovician) in Ayrshire, Scotland.

CHAPTER XV.

Metamorphism.

ANY account of the features of the metamorphic rocks must be prefaced by some reference to structural considerations. Even the question of rock-weathering and sub-surface alteration is closely bound up with the general problem of metamorphism.*

If we consider the materials of the earth's crust, it is



FIG. 97.—MOUNT DARWIN, Mashonaland. A hill of Metamorphic Schists.

obvious that they are subject to conditions which are by no means uniform at different depths. Not only are there the regularly progressive changes of temperature and pressure to be taken into account, but also many local factors of considerable importance, which give rise to great diversity among the agencies promoting change. It will,

* See especially Van Hise's *Treatise on Metamorphism*.

of course, be recognised that a rock is never in a state of even chemical stability. No sooner is it produced than it is subjected to influences which tend to bring about changes of form or substance. At the surface, it may be disintegrated and carried away to the sea—the eventual destination of every exposed particle of the earth's crust. Below the surface, percolating waters carry off various constituents in solution, and deposit them again in fresh situations, the oxidising action of the atmosphere having to be taken into account as an important element in the changes produced. Beneath the permanent water level, leaching and redeposition by upward or downward-flowing currents, aided by variations of temperature, lead to all kinds of replacements, and have as one result the formation of ore-deposits. Deeper still, earth movements and warping tend to bend and crack, or twist and shatter the resistant rock masses, and still lower down the enormous pressure makes them flow almost unresistingly to adapt their form to the forces acting upon them. Finally we reach the depth of potential fusion, where the bending of the superincumbent rocks of the higher, non-plastic layers into anticlinal arches or domes may, by relief of pressure, permit actual melting of the highly heated masses beneath.

We may thus distinguish three different zones in the earth's crust, quite apart from lithological considerations :

- (1) The zone of oxidation and weathering.
- (2) The zone of fracture.
- (3) The zone of flow, including the sub-zone of potential fusion.

By earth movements, molten materials may be forced from the position where they were formed in the zone of flow far up into the zone of fracture, or even extruded at the surface. Lavas represent the strained-off scum of the deep-seated masses, and volcanoes must be largely fed from sub-reservoirs, such as big dykes and sills, rather than directly from the plutonic magmas themselves. But even these last, through corrosion and the submergence of large masses of rock, may appear high up in the zone of fracture, without as a result losing their characteristic features to any great extent on consolidation. Around them there will in such cases be a well-marked zone of

pyrometamorphism, spreading out as it grades off into the rocks of the zone of flow, and with the products of alteration differing somewhat according to the depth of formation. "Lit par lit," or *interlaminar injection*, is characteristic of the lowest parts of the zone of fracture. In such cases granitic material is injected between laminæ or folia of the surrounding schists, sometimes on quite a microscopic scale. Even more completely "mixed rocks" will be formed where diffusion is superadded; these include many "banded-gneisses," etc.

It is usual to discriminate between dynamo- and pyrometamorphic types, but the grading which takes place at great depths renders the distinction a very arbitrary one in the more extreme cases. In general, however, the changes due to dynamic metamorphism are structural



FIG. 98.—TYPICAL FOLIATED STRUCTURE.
Quartz-Schist, Veracity Mine, Rhodesia.
+ nicols, $\times 50$ diam.

rather than mineralogical, and rocks shewing marked development of new minerals are usually to be regarded as somewhat doubtful members of this group. Crushing and shearing by themselves can only destroy original minerals without giving rise to new ones; where the latter are at all conspicuous they must, in the absence of pyrometamorphism, be attributed as a rule to the help of

circulating water, often highly heated. That great structural changes may be accompanied by very slight mineralogical ones is evident from such observations as those of Barrow among the rocks of a much disturbed area in Forfarshire on the Eastern border of the Scottish Highlands.* He expressly notes, as bearing on this important point, that the intense crushing and shearing "has nowhere resulted in the production of a crystalline schist, and not a particle of new brown mica has been met with anywhere. The total length of outcrop of more or less

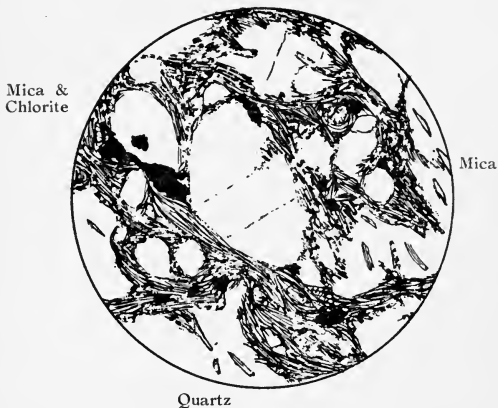


FIG. 99.—QUARTZ MICA SCHIST. Prawle Pt., South Devon, England. $\times 30$ diam.

basic igneous rock is about ten miles. Not a particle of hornblende schist ever occurs in it. Indeed it would be difficult to find an area which seems to shew so conclusively that mechanical deformation alone does not produce crystalline schists."

Of unquestionably mechanical effects, one of the most obvious is the development of slaty cleavage, that is to say of parallel planes of weakness, not necessarily related in

* *Q.J.G.S.*, vol. lvii, 1901, p. 342. Recent experimental evidence seems to shew that pressure has little or no effect in promoting chemical or mineralogical changes.

any way to the original bedding, along which a rock may be readily split into sheets. This is especially conspicuous in the case of argillaceous sediments, in which it may obliterate all traces of the bedding planes, but it is also well seen in certain of the less pure limestones (*e.g.*, those of South Devon, in England) and in some fine-grained sandstones, as well as in a number of ancient tuffs and even volcanic rocks. It results from the squeezing into a roughly parallel position of the various constituents of the rock affected, and is accompanied by the production of minute shreds of mica, chlorite, etc. Where these minerals become prominent enough to give a glossy sheen to the rock, it is often called a *phyllite*, and the structure becomes rather foliated than laminar. In foliation is implied that the constituents of the mass occur in the form of thin leaves, or elongated lenses, overlapping and dovetailing into one another. Rocks like sandstones which resist to a large extent the impression upon them of cleavage, may under the influence of more intense stresses develop a foliated structure and become more or less schistose. Schistose grits commonly shew the development of much mica and chlorite between the squeezed-out lenticles of quartz, these minerals resulting from the alteration of feldspar and other impurities present. By further structural and mineralogical changes, phyllites and other rocks may pass into true *schists*. This is especially the case with rocks which have been subjected to deformation in the zone of flow. They will then consist entirely of new minerals, or, at any rate, of recrystallised ones, and are allied to the contact-altered masses occurring at less profound depths. The last group comprises many of the more typical crystalline schists, and will be referred to at greater length in the next chapter.

The mechanically deformed rocks of the zone of fracture usually consist chiefly of the original constituents or of their *débris*, though such minerals as sericitic mica, chlorite and actinolite are frequently developed. In some cases relatively large lenticular patches and shreds of the original rock may remain embedded in a matrix derived from the breaking down of the rest, a strongly foliated appearance being emphasised by the development of wavy strings of

mica or chlorite along the direction in which the rock has spread at right angles to the pressure. *Crush breccias* and even conglomerates may thus be formed from hard and brittle rock masses. In its extreme form the crushing of such rocks will give rise to *mylonites* in which the original constituents are completely ground to powder.

Metasomatic changes frequently aid in the processes of dynamic metamorphism, and by some authorities are accorded a very prominent place. They consist in the



FIG. 100.—CRUSH BRECCIA, Sebakwe River, Rhodesia.

replacement of one form of mineral matter by another, and undoubtedly contribute largely to the alteration of the older rocks, even those which have been subjected to relatively little disturbance. In its simplest form, *metasomatism* is represented by such processes as the substitution of magnesia for lime, which results in the production of dolomites from limestones, a change which may take place under the influence of sea water alone, as seen in modern coral reefs. It is generally, however, a deep-seated process. It is allied to and accompanied by various

forms of *cementation*, consisting in the deposition of substances like quartz, calcite, iron oxides, etc., among the interstices or pores of all classes of rock. The deposition of silica especially may be of very material consequence. Under the influence of the lateral pressure to which slaty cleavage and often foliation are due, the strata naturally become arched up into anticlines, with corresponding synclines in between. If sufficiently rigid, there is always a tendency for the beds to separate along the axes of the folds, and such spaces become filled as they are formed with minerals like quartz, often accompanied by chlorite, etc., the pressure materially aiding no doubt in the solution of these substances, which are generally leached out of



FIG. 101.—“BANDED IRONSTONE.”

the surrounding mass. In an extreme form such action may give rise to the occurrence of saddle reefs, like the celebrated ore-deposits of Bendigo, but puckering on a minute scale is more important from a petrological point of view. The lenticles of quartz formed in the crests of small folds may materially alter the character of the rock in which they occur.

As examples of changes that must be largely due to metasomatism and cementation we may mention the iron-bearing rocks which are characteristic of almost every Archæan area. They are conspicuous features round Lake Superior and in Canada, as well as in India,

Brazil, Tropical Africa and Western Australia, and are often of great economic importance. They now vary from almost pure quartz to nearly pure iron oxide, but they must originally have been coarse to fine mechanical sediments (sandstones and shales), as shewn by their structural relations and distribution. They are variously known as "ferruginous cherts," "banded jaspers," "magnetic quartzites," "haematite schists," "itacolumite," "banded ironstones," etc., and that their metamorphism has taken place without the aid of very high temperatures is conclusively shewn by their conversion at granite contacts into schists and granulites containing andalusite, fibrolite, hornblende, pyroxene, etc.*

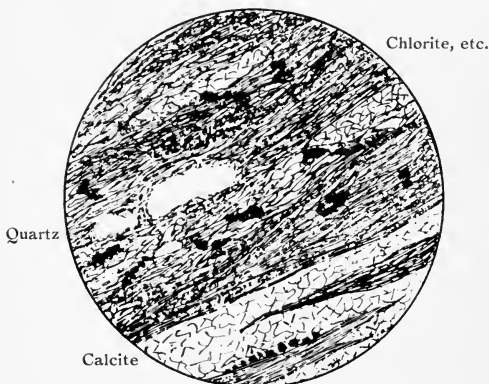


FIG. 102.—CALCAREOUS CHLORITE SCHIST. Due to crushing of Epidiorite along line of fault, Gwanda, Rhodesia. $\times 20$ diam.

For descriptive purposes the term *schist* has been indiscriminately applied to almost every conceivable type of metamorphic rock. It does not necessarily imply a foliated or laminar structure, though this is usually to be observed on weathered surfaces or under the microscope, even when not apparent in hand specimens. Finely foliated structures are chiefly characteristic of the altered

* See Mennell, *Q.J.G.S.*, vol. lxvi, 1910, p. 357.

sediments. Coarsely crystalline rocks are usually to be regarded as originally igneous, and the changes associated with the development of foliation are chiefly paramorphic and probably due, in many cases, to their having been depressed to depths at which the temperature is considerable. The name *gneiss* may be reserved for those felspathic varieties which are allied to granite or diorite in mineral composition ; most of these rocks are, however, the edges of granite masses, shewing a kind of flow structure, or owe their origin to thermal metamorphism. The name of the most distinctive mineral is used as a prefix to give more precision to the terms employed ; thus, chlorite schist, biotite gneiss. *Epidiorite* is often employed for the hornblendic rocks resulting from the metamorphism of dolerites and such like basic types, nearly pure hornblende rocks being termed *amphibolites*. They may be either massive or foliated, though the latter are generally classed as hornblende schists. *Granulite* may be used for rocks with an evenly granular structure, and *epidosite* is applied to highly epidotic rocks ; both of these groups are, however, mostly of " mixed " origin, or due to hydrothermal action at a depth. A number of highly altered but still recognisable sediments give rise to the greatest difficulties in the way of naming. Expediency is the only policy in such cases. Thus, an Archaean rock might be termed either a chloritic gneiss or a crushed sandstone, according as it might be desirable to emphasise its immediate characters or its sedimentary origin. Neglect of such considerations may lead to endless confusion ; in fact, expediency is the only principle that can be followed until a logical classification of the metamorphic rocks is put forward, a task for which the time is not yet ripe.

CHAPTER XVI.

Thermal Metamorphism.

General Considerations. Before considering the structural and mineralogical characters of the remaining metamorphic rocks, it will be well to give some attention to certain questions connected with their origin that have so far been mentioned only incidentally in discussing the genesis of the igneous rocks. Thus it is to be noted that under the head of thermal metamorphism may be grouped processes which in their extreme forms are essentially different, though all gradations are to be observed between those extremes. There have to be considered, first of all, those instances of purely local "contact alteration" by igneous masses projected far above their place of origin, and secondly, that deep-seated and advanced alteration which is the concomitant rather than the result of the formation of great granite masses. It is seldom perhaps that we can actually study the plutonic rocks among the surroundings in which they assumed a molten condition. The great Archaean areas of the globe nevertheless give us an insight into the nature of the alteration which has taken place in situations where the normal depth temperature differed little from that of the plutonic masses which are now exposed to view intruded among the metamorphic types. These latter may sometimes be identified as of sedimentary origin, but they are necessarily profoundly altered by the mere effect of burial at great depths, as depression to even 20,000 feet, which must be a very moderate amount, would mean exposure to a crushing strain of over 70 tons to the square inch at a temperature double that of boiling water. Those cases, therefore, where granite masses have invaded normal sedimentary strata are to be regarded as allied to the conditions of intrusion of ordinary dykes, and the contact phenomena generally differ in degree rather than in kind from the effects of the latter. They are essentially different from what are observed in areas of crystalline schists.

Conditions of Alteration. It might seem obvious enough that the altered rocks in the neighbourhood of igneous masses owe their immediate characters to the influence of intense heat, often accompanied by a certain amount of transfusion of igneous material. But this view is not universally accepted. In the case of granite, indeed, it is sometimes contended that it may be injected at a temperature of only a few hundred degrees centigrade, so that, as far as actual heat is concerned, its powers of alteration would be small. It is argued, however, that the igneous magma contains much more water than is evidenced by the practically non-hydrous condition of the solid rock. On this view the consolidation of the magma would result in the water, together with certain other more or less volatile substances being "forced into the enclosing rock, producing the recrystallisation and rearrangement of its constituents called contact metamorphism." It may be pointed out that the minerals formed round contacts are not any more hydrous as a rule than those of granite itself, but before proceeding to elaborate this point we may notice the arguments that are relied upon in support of the view that granite exists in a state of fusion at low temperatures. Michel Levy's school maintain that granite masses have a core consisting of material consolidated from fusion while the rest is the result of deposit from what are practically aqueous solutions. At a temperature higher than that of ordinary lavas, the constituent minerals would be in a truly molten state, and the fact that the felspars and quartz do not contain vitreous inclusions is adduced against their having been in such a condition. Then, too, certain varieties of granite may contain minerals which, like topaz and apatite, cannot exist under ordinary conditions, at least in the presence of silica, at high temperatures. Others again, like orthite and columbite, are *pyrognomic*, that is to say, change their physical condition on being heated, while orthoclase itself changes its axes at temperatures above 600 degrees, as we see in sanidine. Silica too assumes the form of tridymite on crystallising from fusion under atmospheric pressure, and has a transformation point at about 800° C.

Turning now to the other side of the question, we may point out that it can scarcely be believed that the molten

lavas we see emitted at the surface are hotter than the source from which they draw their materials, and from which they often bring up perfectly formed crystals. The actual temperature of consolidation is of little moment provided the plutonic mass is ever as hot as the erupted lavas, which can scarcely be disputed. The melting points of these last are seldom lower than $1,000^{\circ}$ or $1,200^{\circ}$ C., and they would be unable to flow any distance from the vents through which they rose, unless heated to still higher temperatures. The absence of vitreous inclusions in the minerals of plutonic rocks may surely be attributed to the effects of *pressure*, just as much as the structure of the rocks themselves: indeed, all the arguments we have alluded to overlook the importance of pressure in its effects on crystallisation. We know from actual experiment that calcite, which is split up, under ordinary conditions, by heat, remains chemically unaltered under pressure, even when raised far above the normal temperature of dissociation. *Relief of pressure*, too, has the same effect as *rise of temperature*, and we find that olivine, which is sometimes formed at great depths, becomes *corroded* and even entirely *resorbed* in lavas, like those of Vesuvius; whose highly heated state is a matter of actual observation, and which we cannot suppose to have been cooler underground. We thus see that it is perfectly true that *under surface pressures* there are many minerals which could not form or continue to exist at very high temperatures, but it is equally certain that they *can* form at even higher ones *under increased pressure*.* It is, in fact, only relief of pressure which gives rise to the formation of a magma by allowing fusion to take place.

But there are other considerations of no little importance which must not be left out of account in questions of this kind. If we put, as some writers would do, the consolidating point of granite below the critical point of water, namely, 350° C., how are we to avoid the obvious inference that the mere heating effects of a dyke or lava-flow would involve the formation of a fluid magma, so

* Some recent experiments have been cited as shewing that pressure causes rock magmas to consolidate as glass. This is obviously paradoxical, since observation clearly demonstrates that no natural rocks consolidate as glass, except under small pressures.

that we are faced by a *reductio ad absurdum*. Moreover, we know that hydrous minerals like orthite and muscovite can apparently form in a plutonic rock, so that if water is really of importance in a magma, there is no reason why they should not be present in large quantities, instead of in minute ones, and under circumstances which nearly always give rise to some suspicions regarding their primary origin. Both may, in fact, be due to the concentration at the edge of a mass of the almost infinitesimal quantity of water originally distributed throughout, but arrested on the margin by crystallisation after relief of pressure had allowed some play to its tendency to escape from the more fluid central portions. There is probably some truth in the idea that water assists in contact alteration, though its efficiency as the prime cause of the alteration cannot be maintained in view of the comparative rarity even of epidote, the only hydrous contact mineral of any importance, apart from muscovite, which it is difficult to regard in quite the same light. It is highly probable, too, that the so-called *magmatic water*, which has played an important part in the formation of many ore deposits, is merely the normal water content of the adjacent rocks that has been driven off in front of an advancing igneous mass.

The minerals we actually find in common contact rocks afford us some very interesting points. Thus we have the dimorphous silicate of alumina which crystallises as andalusite with a prism angle of 91° , and also fibrolite with a prism angle of 111° and a higher specific gravity. The form assumed seems entirely dependent on the temperature, andalusite changing to fibrolite at 1350° C. Now fibrolite is not only common in contact rocks, but even occurs at times in normal granites, so that we appear to have direct evidence of the high temperature of these last. Further light has been thrown on this question by the recent researches of Wright and Larsen, who have shewn * that in granites and even in pegmatite veins, the quartz (the last mineral to consolidate) exists in a modification which is only assumed on cooling from over 570° . The fact that we cannot form minerals like orthoclase

* See Iddings, *Igneous Rocks*, vol i, p. 211.

without the aid of water proves nothing ; it appears to be merely due to the impediments put in the way of crystallisation by the high viscosity of the melted substance. We can scarcely hope to reproduce plutonic conditions in the laboratory, owing to the difficulty of maintaining great pressures on substances at a high temperature.

Results Observed. The contact alteration effected by different igneous masses varies remarkably in its extent. We shall here allude only to cases where the igneous magma has penetrated into the upper regions of the crust, and has consolidated among rocks which were comparatively cool prior to its intrusion. Even with this limitation, we find surprising divergences. Some quite insignificant intru-



FIG. 103.—TOURMALINE IN AMPHIBOLITE. Near Umtali, Rhodesia.
× 20 diam.

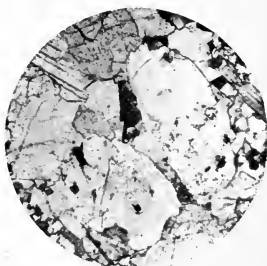


FIG. 104.—SCAPOLITE IN MARBLE. Kafue River, N.W. Rhodesia.
× 50 diam.

sions affect the surrounding strata for considerable distances, while in other cases large masses may only produce noteworthy changes immediately alongside their margins. Of course, much depends on the nature of the enclosing rocks. When these are normal sediments the alteration may be very striking, even if it does not extend far. In the case, however, of rocks previously altered by other metamorphic agencies, the results of contact alteration may often be very obscure, even when the amount of change has really been considerable. This question will, however, be more fully dealt with in the next chapter. It may be noted that in the case of sedimentary rocks at a great depth below the surface, the chilling effect they

have necessarily had on the invading magma has effectually prevented, in the great majority of cases, any marked transference of igneous material into the products of alteration. Chemical evidence is usually decisive on this point. What are termed *pneumatolytic* agencies are sometimes, however, strongly in evidence: these result in the formation of compounds like tourmaline, scapolite, and chondrodite, containing boron, chlorine, fluorine, etc., which are generally assumed to have been given off from the intrusive rock in the form of vapour.*

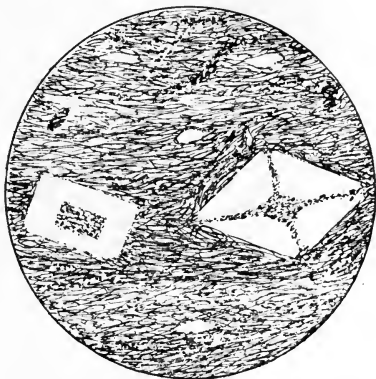


FIG. 105.—CHIASTOLITE SCHIST. Fichtelgebirge.
X 20 diam.

Effects on mechanical sediments. The coarser and purer mechanical sediments, such as ordinary sandstones, are not much changed mineralogically unless a considerable transfusion of igneous material has been effected. They are often, however, almost melted, so that the grains interlock and form a compact mass almost like vein quartz. Where these quartzites have contained such minerals as felspar among their constituents, they may recrystallise, and mica may be developed. The production of fibrolite needles is also frequently seen, and arkoses may even give rise to rocks like a normal gneiss.

* See, however, Chap. XI.

On the finer argillaceous sediments much more striking results are produced round important intrusions. Even at a distance from the igneous rock the formation of chlorite and muscovite is usually to be observed. Nearer we may get the production of biotite flakes and often of staurolite or chiasolite crystals, these becoming increasingly numerous as we approach the cause of the alteration. Closer still, the sedimentary characters of the rock may become entirely lost. Both muscovite and biotite may abound, ordinary andalusite takes the place of the impure chiasolite, quartz and felspar become common, while garnet, kyanite, tourmaline, fibrolite, etc.,

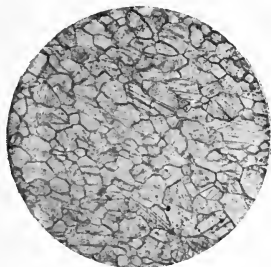


FIG. 106. — WHITE MARBLE, Chillagoe, Queensland, Australia.

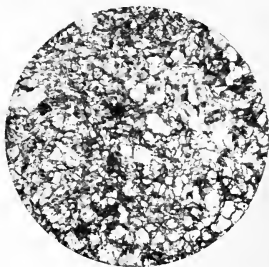


FIG. 107.—WOLLASTONITE-PYROXENE-ROCK, Donegal, Ireland.

often impart distinctive characters to portions of the rock. As bearing on the points discussed above, it is interesting to notice that these rocks become markedly less and less hydrous as the igneous mass is approached.*

Effects on calcareous rocks. The effects of pyro-metamorphism on limestones, etc., may amount to no more than simple recrystallisation, a pure white marble being often the result. If the rock contains silica, or this last is provided by injection of material from the invading magma, various silicates are produced. Wollastonite,

* "With increasing metamorphic intensity, with greater proximity to the granite, the percentage of water in the contact products decreases in a regular and visible manner." Rosenbusch, *Die Stieger Schiefer*, p. 256.

lime-garnet, idocrase, scapolite, epidote, mica, pyroxenes, amphiboles, and even olivines, are thus formed, sphene, apatite, beryl, spinel and corundum being found as accessories. It is probable that many so-called "peridotites" and "eclogites" originate in this way and are not truly igneous, especially as magnesia seems readily transferred even from acid magmas into the surrounding rocks. The hydrous alteration of many rocks of this class gives rise to the formation of serpentines, or "ophicalcites," composed of serpentine with some residual calcite, etc.

Mr. Hutchings describes the production of many of the silicates referred to above, in the case of the argillaceous



FIG. 108.—CHALK, ALTERED BY DOLERITE. Scawt Hill, Co. Antrim, Ireland. Shewing Wollastonite, Zoisite, Scapolite, and Magnetite in clear Calcite.
× 25 diam.

(From *Geological Magazine*, after Gough).

limestones surrounding the Whin sill.* Very similar effects on a more pronounced scale are recorded for the Antrim chalk by Professor Gough.† A wonderful variety of well-developed silicates occur in the ancient crystalline limestones injected by granitic material both in Ceylon and in Northern Rhodesia.

* *Geol. Mag.* 1898, pp. 69-82 and 123-131.

† *Geol. Mag.* 1907, pp. 145-148, with plate.

CHAPTER XVII.

Regional Metamorphism.

WHEN we come to deal with the features of those great areas of the older rocks which are of a consistently metamorphic character, we are confronted with problems of a somewhat different order from those which present themselves in cases of purely local metamorphism. The rocks, of Archaean or presumably Archaean age, which make up such areas, naturally attracted attention in the early days of geology, before the ground had been cleared by patient investigations of simpler geological phenomena. The conclusion was therefore almost inevitable that they owed their peculiar characteristics to deposition under conditions altogether dissimilar from those of later geological periods, and this conception even yet underlies certain of the ideas current regarding them. It is not disputed that they represent masses of igneous and sedimentary origin in a more or less altered condition, but there are nevertheless many important questions which cannot be regarded as finally settled. This is attributable largely to circumstances quite apart from the obvious difficulties in the way of their study. To one we have already alluded—their having attracted so much attention before the elucidation of simpler cases of dynamic and thermal metamorphism had provided means for attacking the larger problems which they present. To this must be added the fact that their detailed study has been principally undertaken in areas where they are only meagrely represented. Thus in regard to the magnificent Canadian development of these rocks, many early ideas have only lately been seriously questioned, while in the exhaustive examination of such regions as the Scottish Highlands, geologists have been handicapped by the relative smallness of the main tectonic features and by the complications resulting from earth movements on a grand scale at a later period than the changes that we

are now considering, as well as by subsequent igneous intrusions.

The rocks of the "Fundamental Complex" in the Highlands of Scotland, have, as Dr. Teall remarks,* in most cases marked affinities with igneous products. Judging from the admirable descriptions of the Geological Survey, they appear, however, to correspond still more closely with what we know from the experience gained in much more extensive areas, to be the contact zones of great granite masses. In the Highlands these granites themselves are not well developed. Moreover, as the crystalline rocks there border upon an obviously unstable portion of the Earth's crust, they have necessarily been subjected to much greater vicissitudes in the way of crushing and shearing than those of the Archaean areas of the much larger and more stable land masses of tropical Africa and North America. This is clearly indicated by the great overthrusts which the work of Nicol and Lapworth has demonstrated to have taken place among the Highland rocks in Lower Palaeozoic times, and of which there seem few traces in Canada or elsewhere. This difference appears to correspond with that which is often insisted upon between *orogenic* (or mountain-building) and *epeirogenic* (or continent-forming) crust movements. There can be little doubt, in fact, that what has been generally termed "regional metamorphism" is, in the majority of cases, much more closely allied with contact alteration than with the results of dynamic processes, though the former may often have been superimposed on the latter. This is particularly well shewn in the African metamorphic region extending from the North of the Transvaal through Rhodesia into the Congo State and Uganda. Among the most abundant rocks of this area (apart from the great intrusive granite masses) are various hornblendic types, often affording no clue in their outward appearance to their original nature. Under the microscope, however, in spite of their complete amphibolisation, they still show in an unmistakeable manner such characteristic features of the basic igneous rocks as ophitic and poecilitic structures. Other rocks of more acid composition have spheru-

* *Mem. Geol. Survey, N.W. Highlands of Scotland*, p. 75.

litic, perlitic and vesicular structures. These last shew how little distortion has taken place since they were originally formed, and the same is the case with the conglomerates which occur intercalated among the other metamorphic types. Their pebbles are seldom much flattened or crushed, and when weathered out from their recrystallised matrix, they might readily pass as of slight geological age. These examples are typical and not exceptional, and it must therefore be concluded that the crushing and shearing generally implied in the idea of dynamic metamorphism played a minor part in the trans-

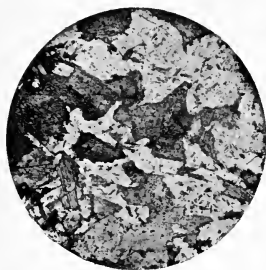


FIG. 109. — EPIDIORITE, retaining an ophitic structure. Near Bulawayo, Rhodesia.
× 20 diam.

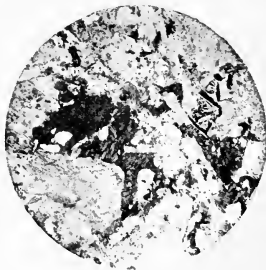


FIG. 110. — EPIDIORITE, with pæcilitic plate of brown hornblende. Westacre, Rhodesia.
× 20 diam.

formation of the rocks of the whole area into crystalline schists. It must not be supposed that the region referred to shews a less advanced degree of recrystallisation than the Scottish Highlands. On the contrary, in some respects the metamorphism of the latter is distinctly less intense, as witness the fact that original augite is still to be detected in the basic rocks of the Highlands, whereas in Rhodesia the examination of hundreds of slides has entirely failed to reveal its presence even in what are obviously the very latest intrusions prior to the formation of the great granite masses, which last may possibly be of Lower Palaeozoic age (though probably late Archaean).

In connection with the structure and features of the

metamorphic rocks, a right understanding of the relationships of these granites is of the first importance. In Africa they are the predominant rocks and the same appears to be the case in Canada. It is not surprising therefore that it was long before their intrusive character was realised in either area. It can, however, be proved by many critical sections, though the differences in the contact phenomena as compared with those of intrusions among normal sedimentary rocks was long a stumbling block to observers trained in European surroundings. This is not to be wondered at: indeed, as the granite masses must have originated from the fusion of materials precisely similar to those of the surviving schists it would seem only reasonable to anticipate that we should see in the field complete gradation between the metamorphic rocks and those of a plutonic nature. This would, no doubt, be the case if we could study the plutonic masses *in situ* at the depth where they had their origin. But deeply as denudation has cut into them, it is evident from the marked alteration frequently to be observed along the margins of the granites that we should have to go deeper still in most cases to reach their actual place of formation. Chemical corrosion and the engulfing of large masses of schist have resulted in the appearance of the granites at higher horizons than those at which they first assumed a fused condition. This would be at least 100,000 feet, or nearly 20 miles deep, if we assume a melting point for granite of about 1000° C., unless we admit excessive local radio-activity as a factor in the problem. At the same time, in the great Archæan areas, we are everywhere much nearer the roots of the igneous masses than in the case of most European occurrences, hence the important differences that are to be observed in the nature of the contact phenomena. The schistose rocks generally have a dome-like structure, the dip of foliation being away from the granites and the strike parallel to their margins. Consequently the upper members of the metamorphic series are not usually seen to be invaded by the granites unless the latter have completely absorbed the basement rocks. Cases, however, do occur where the strike of the schists is into the granite, or the dip towards it. The extent and characters of the contact zones vary greatly. We fre-

quently find that* "the granite masses are bordered by gneisses which are formed by a lit-par-lit injection of sedimentary schists by granitic material." Schists derived from igneous materials are very often similarly affected. Actual dykes are distinctly rare at most contacts, and hardly ever extend much beyond the zone of interlaminar injection. Indeed, they serve principally as feeders for injection processes.† There may, however, be every gradation between large dykes running out hundreds of yards into the schists, and the insinuation of granitic material on a purely microscopic scale between their



FIG. III.—Shewing contrast between contacts of dykes and deep-seated rocks. (Igneous rocks black.)

foliation planes. Sometimes the granitic and sometimes the schistose material forms discontinuous bands or lenticles, and subsequent diffusion has led to the formation of typical banded gneisses. Nearly all of the gneisses, &c., often regarded as the oldest Archaean rocks, may be set down as interlaminar injection products. That they need not be of great antiquity is shewn by their occurrence round such masses as those of Maine, U.S.A., which are of Devonian age.

* G. O. Smith in "Granites of Maine," *Bull.* 313, *U. S. Geol. Surv.*, p. 9.

† Compare fig. in *Summ. Prog. Geol. Surv. U. K.*, 1907, p. 78, and Shand, *Trans. Edin. Geol. Soc.*, Vol. IX., Pt. V. (1910), Plate XXXV.

In describing the features of the Archæan areas of Malvern and Anglesey, Dr. Callaway distinguishes between what he calls primary and secondary injection. Both these processes are well observed in the case of the Rhodesian granites, if we rightly apprehend his meaning. Thus a very common and characteristic feature of ordinary injection is the occurrence of an acid felspar like microcline among the constituents of a thoroughly basic rock. But, besides these cases of simple injection of fused material along foliation planes, we have good examples of what may be termed secondary injection. That is to say, we notice development among the schists of minerals like epidote, zoisite, chlorite, and quartz, formed, it would seem, under the influence of heated waters, driven off from the materials absorbed into the magma, or evolved during its crystallisation, or even perhaps by the action of water which percolated down towards the cooling but still hot mass after its consolidation. Splendid examples of such rocks occur along the northern margin of the Matopo granite, in Rhodesia, at the point where it is crossed by the Gwanda railway line.

It will readily be observed how very indefinite some of these granite-schist contacts really are. One may start, as is the case near Bulawayo, on massive, coarsely crystalline epidiorites with distinct traces of an original ophitic structure, which shews that they were formed by the metamorphism of dolerites. As one approaches the granite they assume a more and more foliated character, and acid igneous material makes its appearance between the laminae. This gradually increases in abundance until we have half igneous, half metamorphic, banded gneisses, and these merge into granite full of hornblendic inclusions and bands. Further inside the granite the inclusions become less and less distinct, and we pass through hornblendic granite into the normal biotite-bearing variety. It becomes extremely difficult in the detailed mapping of such areas to decide upon a boundary line for the granite. This has been noted for instance, by Messrs. Emerson and Perry,* who state in the case of Rhode Island, U.S., where similar conditions prevail that

* Bull. No. 311, *U.S. Geol. Surv.* (1907), p. 46.

"a broad area between granite and schist could be mapped only as a contact zone between the two." Almost identical features have been described by Dawson in the case of Canadian granites intrusive in strata as late as the Triassic period.* Sometimes, however, the boundary between granite and schists is perfectly definite, in which case the granite preserves its normal structure right up to the edge. The same mass may present very different features at different points. Thus the comparatively small isolated Heany mass, east of Bulawayo, has a sharply defined boundary to the north, with an abrupt transition from normal granite to normal schist. To the

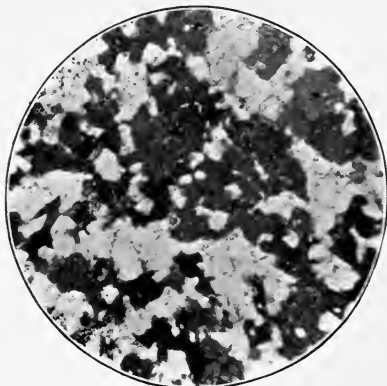


FIG. 112.—GRANULITE. From Granite-hornblende-schist contact zone. Figtree, Rhodesia. $\times 30$ diam.

south, however, there is an area of "mixed rocks" more than equal in extent to the whole of the normal granite. These "mixed rocks" include small patches of granite and schist inextricably mixed up with types of rock which would be classed by many authorities as diorite, quartz-diorite, monzonite, aplite, pegmatite, quartz porphyry, felsite, gneiss, granulite, &c. As a matter of convenience,

* *Rep. Geol. Surv. Can.* (1887), part B, p. 11. See also Adams, *Q. J. G. S.*, vol. 64 (1908), p. 133.

however, in view of the fact that it is very doubtful whether any of them have really crystallised freely from a state of true fusion, these rocks are perhaps best all grouped together for descriptive purposes as *granulites*, a course which has the justification of their shewing under the microscope a characteristic evenly granular structure in most cases.*

Mineralogical Transformations. In extreme cases, all indications of the original constitution of metamorphic masses are lost. This is especially the case where dynamic agencies have been most effective. Frequently, however, they can be traced with considerable accuracy as a result of careful investigation. Some sedimentary rocks, even when occurring as actual xenoliths in granite, preserve

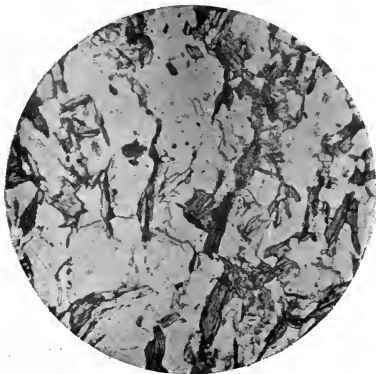


FIG. 113.—MICA SCHIST, Menaggio, Lake Como, Italy. $\times 20$ diam.

features which lead to their recognition as such. Thus characteristic "contact" minerals like the silicates of alumina often persist, though perhaps there may be instances where they really result from the melting of igneous materials like mica. The last term in any series

* For further information on these points, see Mennell, *Q. J. G. S.* vol. clvi. (1910), pp. 362-4.

of changes is the formation of a rock containing feldspars and the assumption of the habit of a plutonic rock. The other stages are only preserved for us when comparatively rapid cooling intervenes before this term is reached, and may be compared with what is observed in the study of artificial metallic alloys, although the time involved is very different. There is another important factor in these changes, and that is injection. A very small amount of diffusion subsequent to the injection of granitic materials into a sediment will obliterate all traces of its original character and lead to the formation of the ordinary feldspars and ferro-magnesian minerals instead of the highly cal-

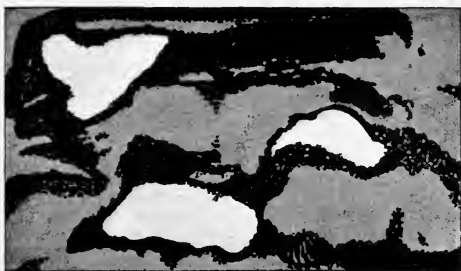


FIG. 114.—OCCURRENCE OF CORUNDUM. Tuli district, Rhodesia. (*About half scale*). Feldspathic Matrix, shaded ; Magnetite and Spinel, black ; Corundum, light.

careous or highly aluminous silicates typical of rocks altered by small intrusions.

To particularise more fully regarding mineralogical changes we may take the common type of sediment represented by ordinary shales. These first develop chlorite and epidote, often accompanied by mica and by quartz separated in the course of the formation of the previously mentioned minerals from less basic silicates. If they are depressed to a considerable depth without the temperature reaching near that of an igneous rock, and with access of circulating water, they tend to lose most of their bases and to become transformed into the flinty-looking banded iron-bearing rocks so common in every

Archæan area. Where, however, the changes are predominantly dynamic we get finely fissile slates and phyllites, passing into chlorite and mica schists, the latter rich in quartz as opposed to felspar. Where thermal agencies act upon these or less altered rocks, two types of metamorphism are possible. We may get andalusite etc., formed from the mica or direct from clayey substances, the quartz still remaining largely unaffected, or else reactions may be set up between the quartz and mica, resulting in the production of felspars. The latter process probably implies freer migration of molecules, and is certainly more and more conspicuous the higher the temperature involved. Nevertheless andalusite, kyanite, staurolite, cordierite, fibrolite, spinel and corundum



FIG. 115.—SPHENE. With enclosures of Rutile and Magnetite. In hornblende granulite, near Fort Jameson, N.E. Rhodesia. $\times 100$ diam.



FIG. 116.—SPHENE. With residual ilmenite; in Epidiorite. Between Rifle Kopje and Khami Road, near Bulawayo. $\times 100$ diam.

persist remarkably when transfusion is at a minimum, and indeed may even appear locally as accessory constituents in granite masses. Bands and patches of hornblende and pyroxene granulites or gneisses may be found in many granites where the assimilation of sedimentary or other foreign material is not quite complete. The highly artificial nature of the distinction between igneous and metamorphic products is admirably illustrated by the brilliant researches of Morozewicz, who produced by simple fusion such characteristic "contact" minerals as corundum, spinel, cordierite, fibrolite, etc.

Taking quite another class of rock we may instance the common epidiorites of Archæan areas. These were no doubt dolerites and allied igneous intrusions in their original state. Under the influence of mere static pressure, aided by circulating water, the augite is transformed into

hornblende, sometimes without any marked structural changes. Under dynamic influences they are altered into chloritic schists, usually with development of much calcite. On the other hand, extreme thermal action results in the reproduction of augite from the uralitic hornblende, while the original ilmenite is transformed into granular sphene. Further alteration, usually seen only in xenoliths, or immediately along contacts, produces hornblende granulites. In these pyroxene (including enstatite) and mica often coexist with the hornblende,



FIG. 117.—HORNBLLENDE-AUGITE-GRANULITE.
Near Sikale's Kraal, Matopos, Rhodesia.
× 20 diam.

though they seldom rise to the position of dominant constituents. The composite origin of many of these rocks is well illustrated by the fact that they may contain acid feldspars like microcline and are seldom free from quartz although the water-clear grains of plagioclase are readily shewn by Becke's method to be andesine or a more basic variety. Sphene, in rather rounded crystals, is a constant accessory, while iron oxides, on the other hand, are seldom conspicuous. Rutile sometimes accompanies the sphene and may then occur as an enclosure in it. The introduced acid materials may occur in distinct streaks,

lenses or knots, often visible and indeed conspicuous in hand specimens, or they may be evenly distributed through the whole rock. They also sometimes have all the appearance of porphyritic crystals embedded in the original basic material as a groundmass. This is even seen among invaded sediments and is beautifully illustrated on the Lion's Head and at Sea Point, near Capetown, amongst the altered slates which surround the granite there.*

Special minerals like tourmaline are often found along the margins of small granite masses and minor intrusions. These, like the so-called "magmatic water" seem to represent the more volatile materials of the rocks invaded by a granite mass, materials too volatile in fact to be readily retained in the process of assimilation. They are seldom far found inside the boundaries of really large granite masses, or even along their immediate contacts, only being conspicuous as a rule at a distance of some hundreds of feet or yards from the granite. Epidote is more characteristic of the actual contact zone, though often absent, and by no means certainly an original mineral. In the case of crystalline limestones, scapolite, chondrodite, etc., may be found even in xenoliths. Limestones, by the way, appear to be remarkably insoluble in granite magmas and persist as recognisable xenoliths even when various types of associated rocks have completely vanished. Their organic matter and perhaps additional carbon reduced from the carbonic acid displaced by silica often tends to accumulate as graphite at or near contacts.

It has already been stated that in extreme phases of alteration there is no trace of original characters. The difficulty of discrimination between altered sediments and altered igneous products is rendered obvious by the fact to which Professor Adams first drew attention, in the Canadian Laurentian area, that precisely similar hornblendic rocks ("amphibolites") can be shewn to result from three different classes of rock. In Rhodesia the same fact is apparent. Some of the amphibolites are

* The writer is much indebted to Prof. A. Young, of Capetown, for kindly pointing out the fine exposures of "mixed rocks" on the Lion's Head.

altered igneous rocks (epidiorites). Others are altered limestones, while others again result from the alteration and injection of the type of rock known locally as "banded ironstone," which represents, as already indicated, a shaly sediment, probably first transformed by pressure into slate, as there are at times indications of what appears to be original bedding, quite independent of the banding which is now its most conspicuous feature. Though rarer, pyroxene granulites also originate from each of the same three classes of rock.

Variations of the Granite Masses. The central portions of most Archæan granite masses are remarkably uniform in character, and the various masses differ little from one another. They are typically biotite-bearing grey granites of medium grain, with microcline as the dominant feldspar and subordinate oligoclase. Round their margins, however, they become heterogeneous, varying both in composition and texture to a considerable extent. A gneissic structure is frequent, but the absence of deformation in the minerals of prior consolidation, although the quartz and potash feldspars are often granulitic, shews that the appearance was acquired before the granite solidified. Orthoclase frequently replaces microcline in these marginal modifications, and a plagioclase may become the dominant feldspar. The character of the modifications is obviously connected with the nature of the rocks invaded. Thus, where the granite is adjacent to the epidiorites, it usually becomes more basic towards its edges, and carries hornblende in addition to, or to the exclusion of, biotite. Sometimes it even merges locally into what may be regarded as a diorite. It may be noted, too, that the similarity or identity of the minerals in acid and basic modifications cannot be adduced to prove that they originated from segregation, as the whole of the marginal zones or small masses in which such variations occur differ throughout from the normal central portions of the larger masses in such features as abundance of plagioclase, substitution of orthoclase for microcline, and frequently of hornblende for biotite, as already described.

On the other hand, recognisable inclusions of hornblendic rocks which have reached a position a considerable distance within igneous masses tend to become transformed

into granulites rich in biotite, though often retaining some residual hornblende. This is evidently a prelude to their complete assimilation. The distribution of the various modifications seldom shews any marked regularity. It is always patchy, and if a particular line of section be taken, one passes over a succession of alternations of acid and basic varieties, which, however, become less and less sharply defined as one proceeds inward. One is generally most struck by the basic modifications, and indeed these are usually prominent near epidiorite contacts, but even then are seldom found nearest to the edge. They are

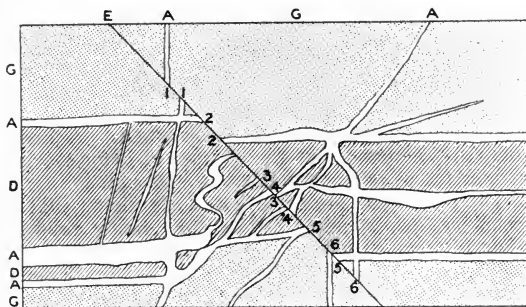


FIG. 118.—Diagram shewing modifications of Granite at Khami Ruins, Rhodesia. Scale 1 inch to 1 foot.

E = Epidiotic vein along a fault; G = Normal Granite; A = Acid Veins; D = Dioritic Vein. The ends of the acid veins on both sides of the fault are numbered to correspond. Note faulting of No. 1 the reverse way to the others.

usually separated from the schists, which supplied much of their material, by bands of more acid granite. This latter seems to eat a way along planes of weakness behind large masses of epidiorite or schist, and eventually detach them from the main body. They are thus set adrift in the granite, by which they are gradually absorbed. Injection and more or less complete fusion without assimilation transform them into quartz diorite, as Prof. Cole pointed out many years back. As regards acid variations, such as "aplite" and "pegmatite," which are frequently termed segregation veins, the field evidence is

decidedly against segregation *in situ* at least. They frequently occur as narrow seams, sometimes only a fraction of an inch in width, yet running in a straight line for great distances—miles in some cases. They must therefore have filled cracks in the already solid rock, and they seem due to processes closely akin to the formation of quartz reefs and mineral veins generally. Indeed, the quartz reefs in the mixed rocks often contain felspar and are very often full of little needles of tourmaline, which give them a bluish tinge.

CHAPTER XVIII.

The Alteration and Weathering of Rocks.

LOGICALLY, perhaps, the subject of the present chapter should precede the discussion of the more complete changes which we have included under the head of metamorphism. They form, however, parts of a different cycle, and are best considered independently, the more so as considerable confusion exists in the minds of many geologists with regard to the products of what we shall here distinguish as *metamorphism* proper, underground *alteration* processes and ordinary surface *weathering*.

It is evident, of course, that all rocks at or near the surface are undergoing more or less complete changes according to their nature and to the climatic influences they are subjected to. These changes are partly physical, and partly chemical, and may be referred to under the heads of *disintegration* and *decomposition* respectively. The former is practically confined to the actual surface, the latter may take place at any depth down to the ground-water level, below which the changes are of a different character. It is desirable in this connection to bear in mind what the student of ore deposits calls the "oxidised zone" and the "sulphide zone." Sulphides are of no importance in ordinary rocks, but a clear conception of the principles underlying the mode of sub-division found so convenient and so essential in discussing ore-deposits is of great assistance in elucidating certain petrological problems. It is unfortunate that the rock specimens chosen for analysis are not more frequently collected from places where mining operations give access to material genuinely unaffected by weathering processes. Indeed it is only possible to discriminate between the alteration products of deep-seated and superficial agencies respectively, by the examination of rocks from situations out of reach of the latter. For even below water-level alteration does take place, and may simulate the action of more

powerful dynamic and other agencies, in which, indeed, similar processes no doubt assist.

WEATHERING. The changes which take place in weathering are always largely due to oxidation and to the effects of water and the substances it carries in solution. It therefore results in the resolution of the rocks concerned into such chemically simple compounds as oxides, hydrates and carbonates. The character of the changes, however, varies considerably in different climates. In



FIG. 119.—GRANITE. Shewing Cavities due to Corrosion by Decomposed Organic Matter. Matopo Hills, Rhodesia.

England, most of the rocks are very rotten at or near the surface, and, in the absence of artificial exposures fresh specimens may be very difficult to obtain. The expansion, in freezing, of water which has penetrated into joints, cracks, &c., is the chief disintegrating force and operates to a considerable depth, while the moist atmosphere promotes chemical changes. In countries like India, tropical Africa, and Northern Australia, the conditions are quite different. Frost is eliminated as a disintegrating agent, and the sun's heat, together with alternating periods

of dry and wet weather, have the most important effects. Where there is no covering of soil, a thin coat of powdery decomposition products, or a surface from which the ferromagnesian constituents have been partly removed, may be all that hides the perfectly fresh rock, the altered portion being no more than a very small fraction of an inch in thickness. Even such susceptible minerals as olivine, nepheline, and melilite may be found as fresh as on the day of their formation in specimens knocked off an outcrop. Indeed, as Mr. T. H. Holland has pointed out for India,* and as workers in the Tropics find from their own experience, special precautions are necessary in pronouncing as to the presence or absence of olivine in many rocks where it shews no signs of alteration. In tropical countries, rock weathering probably proceeds at least as fast as in England, but there the alteration products tend to remain at or near their place of formation for extended periods, while in hotter climates the torrential rains and other agencies promote their speedy removal, except in depressions which are liable to become waterlogged. In such circumstances there accumulate under the soil the "laterites," both ferruginous and aluminous, and the calcareous tufas, which are so abundant in tropical regions. The soils adjacent to or even actually overlying these products are often almost wholly deficient in the constituents concentrated so close to them, e.g., in the Mayse-
Marzoe
 district of Rhodesia.

Owing to the lack of attention bestowed on the subject, there are considerable differences of opinion as to the circumstances under which particular minerals are produced. It is unnecessary, however, to discuss the question at length here.† There seems little room for doubt that serpentine, talc, epidote, zoisite, chlorite and the zeolites are never the result of simple surface weathering, but are due to comparatively deep-seated changes or to hydrothermal agencies. Thus some of the Rhodesian picrites are altered to serpentine at whatever depth a specimen may be taken,‡ while the parts where there is no

* *Geol. Mag.*, 1899, pp. 30, etc.

† See Merrill's *Rocks, Rock-weathering, and Soils*; also several papers in the *Geol. Mag.* for 1899.

‡ Mining operations often allow of this being done several hundred feet below the surface.

serpentine at a depth shew none in weathered specimens. The same is the case with talc and with the epidote that characterises many granulites, dolerites, etc. Uralitic hornblende may sometimes be produced in a way similar to that of the more normal chlorite of the zone of fracture, but it is oftener the result of thermal metamorphism.

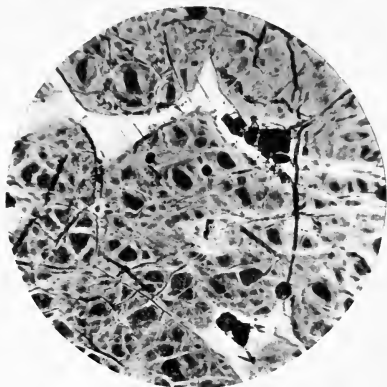


FIG. 120.—SERPENTINE, derived from a rock composed of olivine, with interstitial enstatite.
Nr. Charter, Rhodesia. $\times 30$ diam.

Among the more common products of the alteration *en masse* of rocks may be mentioned the *serpentines*, which are often produced by the hydration of the picrites and their allies; the *epidosites*, which result from the alteration of igneous rocks and occasionally of schists rich in lime silicates; the chloritic and hornblendic rocks ("diabases," etc.) resulting from dolerites, etc.; also certain crystalline limestones and talcose rocks. These latter classes are often difficult to distinguish from the products of more powerful metamorphic agencies, but their study is of much interest as throwing light on the question of more complete changes.

In the case of the serpentines, those which have had their structure obliterated (picrolite, etc.) are to be ascribed rather to dynamic metamorphism than to the class of

changes we have been discussing. Some, however, have altered without losing all traces of their original appearance, and their former constituent minerals may often be identified. The alteration may go even further without obliterating the original structure altogether, and one may find dolomites, traversed by strings and patches of quartz, which still preserve the appearance of ultrabasic igneous rocks (*e.g.*, at Selukwe in Rhodesia). The epidiosites are of considerable interest. A beautiful rock of this type, pink and green in hand specimens, occurs as an alteration product of the Bulawayo granite. The hornblende and

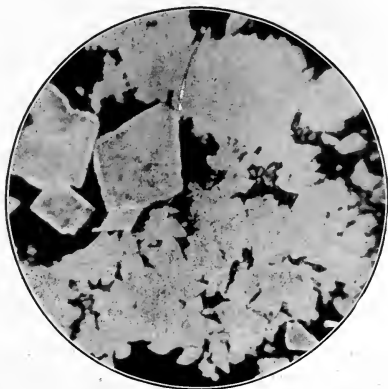


FIG. 121.—RE-CRYSTALLISED DOLOMITE. Near Pretoria Transvaal. $\times 40$ diam.

lime-bearing feldspar (oligoclase) have been entirely replaced by epidote, which, with the primary and some additional secondary quartz, forms a matrix for the almost unaltered microcline of the original rock. This resembles the so-called "unakite" of the United States. The well-known thulite-rock of Trondhjem, in Norway, is of a similar character, but contains the strikingly pleochroic manganese-bearing zoisite, called thulite, instead of epidote.

Certain limestones and dolomites have become highly

crystalline without undergoing changes of the nature of advanced metamorphism. Thus even the matrix of the English Oolitic limestones is often recrystallised, and many of the Carboniferous and Devonian rocks are quite crystalline. A good example of a highly magnesian rock which is often recrystallised, is the Transvaal dolomite (see figure). This is normally an oolitic type. The crystalline structure shewn by many of the Northern Rhodesian limestones

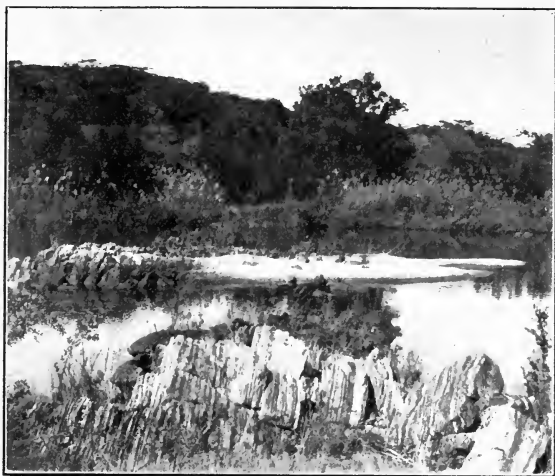


FIG. 122.—“BANDED IRONSTONE,” in the bed of the Sebakwe River, Rhodesia.

(apart from those immediately adjacent to the granite masses) seems to be largely a surface phenomenon. Thus the white marble of the Broken Hill mine is found at a depth of 100 feet to assume the appearance of a compact red or black limestone precisely similar to those of the Devonian or Carboniferous systems in England, though distinctly schistose in microstructure.* Similar processes have no doubt helped in the silicification and impregna-

* See Mennell and Chubb, *Geol. Mag.*, Dec. v, vol. iv., 1907, p. 145.

tion with iron of the "Banded Ironstones" which are prominent features of most Archæan areas, and which are unquestionably altered mechanical sediments. These often become much less hard and flinty when followed down from the surface in the course of mining operations.

The changes produced in surface weathering are more complete, but though they are most interesting, their study is beset with difficulties owing to the impossibility of identifying microscopically most of the minerals produced. Specimens so affected are the bane of the petrographer, as he is often called upon to express opinions on their original nature, a task which may be quite beyond his powers. Experience, however, goes a long way in such cases, and many specimens pronounced hopeless by a novice will yield valuable results to a more experienced eye.

CHAPTER XIX

The Chemistry of the Rocks.

A VERY little consideration will show that ordinary rocks must contain practically all the elements known to the chemist, though the concentration of many of the latter in appreciable quantities is very exceptional. In recent years much accurate chemical work and more especially the admirable analytical results obtained in the laboratory of the United States Geological Survey have, however, shown that the number of substances which commonly exist in determinable amounts is much greater than had been supposed.* At the same time, it has brought to light the fact that some of the elements formerly regarded as rare are, comparatively speaking, abundant and widely distributed, while others, among them some of the most familiar metals, are relatively rare. For instance, titanium is far more abundant than copper, while such elements as vanadium seem distinctly commoner than lead or zinc. Of course, very much smaller amounts than those usually regarded as determinable are of importance, especially to the student of ore deposits. Gold is profitably extracted from lodes where it is concentrated only to the extent of 1 part in 100,000, while even 1 part in a million means more than 10,000 tons per cubic mile, the last a unit quite insignificant when the bulk of the earth's crust is taken into account. Manganese, copper and nickel are frequently each present to the extent of at least one part in ten thousand in perfectly "unmineralised" rock masses. Such masses would therefore in a single cubic mile contain more than the whole world's production of any of those metals for a year.†

* See Hillebrand, *Bulls* 148, 176, and 305 U.S.G.S., especially the last; Clarke, *Bulls* 78 and 330; and Washington, *The Chemical Analysis of Rocks*, 1904.

† Mennell, *Miner's Guide*, p. 14.

It has already been pointed out that the igneous rocks consist in general essentially of silicates, with in many cases an excess of uncombined silica in the form of quartz. Iron oxides, and more rarely, alumina, also occur at times, though far more rarely; nevertheless the basic rocks are seldom to be regarded as such in the strictly chemical sense that the acid ones are, as even in the most extreme cases they seldom contain more than an insignificant excess of uncombined bases. The minor or "accessory" mineral constituents of the rocks are not always silicates, and though they seldom make up any large proportion (say even one per cent.) of a rock mass, they are of much interest as the only source of many of the elements.

Average Composition of the Rocks.

Several attempts have been made to calculate the average composition of the rocks, and thus of the known crust of the earth. Most of them have been of an "arm-chair" order, but the problem is of sufficient interest for the results to be noticed here. Thus F. W. Clarke has attempted, by collating all the analyses made in the U.S. Geological Survey Laboratory to arrive at a general average, with the results given in the appended table.

RESULTS OF ANALYSES OF IGNEOUS ROCKS

(from *Data of Geo-Chemistry*).*

Sub- stance.	No. of De- terminations.	Average.	Reduced to 100 %.	In Elementary form.	
SiO ₂	. 1358	. 60.91	. 59.87	Oxygen (O)	47.09
Al ₂ O ₃	. 912	. 15.28	. 15.02	Silicon (Si)	28.23
Fe ₂ O ₃	. 961	. 2.63	. 2.58	Aluminium (Al)	7.99
FeO	. 962	. 3.46	. 3.40	Iron (Fe)	4.46
MgO	. 1027	. 4.13	. 4.06	Magnesium (Mg)	2.46
CaO	. 1215	. 4.88	. 4.79	Calcium (Ca)	3.43
Na ₂ O	. 1268	. 3.45	. 3.39	Sodium (Na)	2.53
K ₂ O	. 1265	. 2.98	. 2.93	Potassium (K)	2.44
H ₂ O—	. 770	. .41	. .40	Hydrogen (H)	.17
H ₂ O+	. 832	. 1.49	. 1.46	Titanium (Ti)	.43
TiO ₂	. 870	. .73	. .72	Zirconium (Zr)	.026
ZrO ₂	. 185	. .03	. .03	Carbon (C)	.14
CO ₂	. 469	. .53	. .52	Phosphorus (P)	.11
P ₂ O ₅	. 884	. .26	. .26	Sulphur (S)	.11
S	. 575	. .11	. .11	Chlorine (Cl)	.07
Cl	. 234	. .07	. .07	Fluorine (F)	.02
F	. 73	. .02	. .02	Barium (Ba)	.089
BaO	. 617	. .11	. .11	Strontium (Sr)	.034
SrO	. 520	. .04	. .04	Manganese (Mn)	.084
MnO	. 899	. .10	. .10	Nickel (Ni)	.023
NiO	. 243	. .03	. .03	Chromium (Cr)	.034
Cr ₂ O ₃	. 246	. .05	. .05	Vanadium (V)	.02
V ₂ O ₅	. 40	. .03	. .03	Lithium (Li)	.01
Li ₂ O	. 550	. .01	. .01		
		101.74	100.00		

I have criticised the application of these results to the calculation of the average composition of the earth's crust on the ground that no allowance is made for bulk, and they are therefore wanting in one of the essentials of the problem from a mathematical standpoint. This would not be of much consequence if the various classes of igneous rock all comprised masses which varied in size within the same limits, but such is obviously not the case, for there are none in the other classes which approach in bulk the great granite masses of the acid division. The constituents of the acid rocks are therefore given far too little

* F. W. Clarke, *U.S. Geol. Survey Bulletin* 330, p. 26, 1908.

weight, while the importance of the basic group is much overestimated.* This is fully borne out by analytical work on the sediments, where magnesia is much too low and potash too high for Clarke's calculations to be correct. The accurate analytical data, however, are in themselves of great value, and may be applied quantitatively provided due regard is had to their limitations.

For most purposes it might not appear at first sight at all necessary to determine the rarer constituents, which altogether seldom make up more than one or two per cent. of a rock. It is, however, more important than might be thought. For instance, if titanium and phosphoric acid are neglected, the error falls chiefly on the alumina, and so, when the latter is used for calculating the amount of the feldspars, an error of several per cent. may easily be introduced, as Hillebrand points out.

The following is a brief *résumé* of the occurrence of the principal elements in the rocks. Many interesting particulars are derived from the works of Clarke, Washington and Hillebrand already cited.

Oxygen.—This is by far the most abundant of all the elements, forming nearly half of the earth's crust. All ordinary rocks contain between 45 and 53 per cent. of oxygen. It is interesting, therefore, to note that its occurrence in the sun appears to be doubtful. Nearly all the constituents of the igneous rocks are oxygen compounds, sulphur, chlorine, and fluorine being the only determinable elements which form non-oxygen-bearing compounds.

Silicon.—According to Clarke this element forms over 28 per cent. of the igneous rocks, and his figure is doubtless considerably below the mark. Nearly all the rock-formers are silicates, magnetite, ilmenite, chromite, and apatite being the only ones which are of real importance apart from quartz and the other silicon compounds. Clarke estimates that quartz forms 12 per cent. of the igneous rocks, but it must surely reach nearly double that figure, say 20 per cent. His figure for sandstones is 66.8, and for shales 22.3.†

* See pp. 104, etc. ; also *Geol. Mag.*, Dec. V, vol. i., 1904, pp. 263-4.

† *Data of Geo-Chemistry*, Bull 330, U.S.G.S., 1908, p. 30.

Aluminium is third in order of abundance among the elements, and is very evenly distributed among the rocks of all classes, from acid to basic. Only a few ultrabasic types contain little or none of it. Clarke gives the average figure as about 8 per cent. of the metal, equivalent to over 15 per cent. alumina. It is, of course, by far the most important metal, being at least twice as abundant as iron. Apart from the fluorides, only oxidised compounds of aluminium occur in nature. In rock-weathering alumina tends to remain behind among the *débris*, while more soluble substances are removed, and its percentage thus undergoes an increase. In tropical countries laterite, which is frequently to be regarded as an impure form of bauxite, is one of the commonest superficial deposits, for this reason. The feldspars and the feldspathoids are among the rock-formers richest in alumina, while it also enters into the composition of many augites and hornblendes, and of all the mica and chlorite groups. Other aluminous minerals are corundum and the spinels, cordierite, andalusite, fibrolite, kyanite, and staurolite, the garnet group, topaz, tourmaline, etc.

Iron is probably less common than most estimates assume, but it is nevertheless a very abundant and widely distributed element. It enters with lime and magnesia into the composition of the biotite, hornblende, and augite groups, and also to a less extent into that of olivine, while its oxide occurs as magnetite, as well as in ilmenite and chromite. Metallic iron is found in meteorites and also occasionally in basalts. The weathering of the ferro-magnesian minerals gives rise to the iron oxides which occur as colouring and cementing materials in sandstones, shales, etc.

Calcium is perhaps the next most abundant element, though both of the alkali metals have strong claims to be regarded as commoner than either calcium or iron. It occurs principally in the plagioclase feldspars and in the pyroxenes and amphiboles. Garnet, melilite, scapolite, idocrase, wollastonite, epidote, and apatite are other lime-bearing minerals of the igneous and metamorphic rocks. From the decomposition of the lime silicates and the replacement of their silica by carbonic acid from the atmosphere we get the calcite and dolomite of the

limestones. Fluor and gypsum are also important calcium compounds.

Magnesium.—This metal occurs, like calcium, in the pyroxenes and amphiboles, where lime generally predominates over magnesia. It is also an important constituent of olivine, into the composition of which lime does not enter, and of mica, in which lime is rare. Talc, chlorite, and serpentine are important metamorphic derivatives of these minerals, while dolomite is the chief magnesia-bearing sedimentary rock.

Sodium.—The two alkali-metals, sodium and potassium, have been calculated to make up about 5 per cent. of the earth's crust, and sodium is generally considered to be the more abundant of the two, though this is perhaps open to question. It is an important constituent of the plagioclase feldspars, and is rarely altogether absent from orthoclase or microcline. It also enters into the composition of certain varieties of pyroxene and amphibole, as well as of nepheline and the sodalite group. Much of the soda resulting from weathering processes accumulates in the sea as chloride, while to a less degree it gathers in "pans," etc., as carbonate.

Potassium is an important constituent of the feldspars, especially orthoclase and microcline. It also occurs in the micas and in leucite. Small amounts are found in most amphiboles.

The above comprise the more abundant elements. The remainder are of less importance, though many are constantly present in all classes of rock in determinable quantities.

Hydrogen.—Hydrogen chiefly occurs as the well-known oxide water. In rock analyses it is often recorded in two forms, that driven off at or near 100° C., and that requiring higher temperatures. In the table the former is indicated by a minus sign. It is principally due to weathering and to absorption of moisture, and gives too high an estimate of what is really present in the earth's crust. It is unfortunate, for this reason, that rock analyses are not more frequently made from specimens obtained below the superficial zone of oxidation. Even the quantity driven off at higher temperatures is in excess of the probable amount present in rock magmas. Water

exists in combination in the micas, chlorites, epidote, talc, serpentine, chloritoid, etc.

Carbon.—As in the case of water, the amount of carbonic acid recorded in analyses of the igneous rocks undoubtedly leads to an excessive estimate of its abundance among them; but, on the other hand, large quantities occur in the atmosphere, and, derived from it, in the sediments. Cancrinite contains it, and graphite occurs occasionally as a rock-former. The diamond, though so rare, is worth mention as an original accessory constituent of the peculiar type of ultrabasic rock known as "blue ground" in South Africa.

Titanium is one of the ten most abundant elements. In the analyses recorded by Clarke for the United States .73 per cent. was the combined average for TiO_2 , while Washington's computation for the world generally is higher, 1.039. The element occurs in all classes of rocks, but in the more acid rocks it forms sphene, while the more basic ones have ilmenite, or occasionally perovskite. In the great majority of rocks TiO_2 does not exceed one per cent., but in certain basic types it may reach considerably higher figures. Besides the minerals mentioned, it sometimes enters into the constitution of augite, hornblende, biotite, and garnet. Rutile is found in many metamorphic rocks.

Zirconium.—This element is much less abundant than titanium, and occurs as zircon in the more acid rocks and those high in alkalis. Its proportion is usually under .05 per cent., reckoned as ZrO_2 , and seldom reaches 2 per cent. The character of the common "pleochroic halos" round zircon shows that it often contains radioactive substances, chiefly of the uranium-radium series.

Vanadium probably occurs in certain pyroxenes, hornblendes and micas, as well as in ilmenite, and is thus more common in basic than acid rocks. Many basalts and dolerites, such as those of Skye,* have .02 or .03 per cent. of V_2O_3 , and occasionally there is sufficient to affect the figures for Fe_2O_3 if it is not separately determined. Many Australian clays and coals have been shewn by Mingaye to contain up to .1 per cent. or even more of V_2O_3 .

* See Pollard's determinations, *Summ. Prog. Geol. Surv.*, 1902, p. 60.

Molybdenum generally occurs in less amounts than vanadium, but as it is chiefly found in the acid rocks it may be more common on the average, in spite of the lower figures. In any case it is much more often found concentrated in ore deposits.

Chromium.—This element is rarely detected except in the most basic rocks, but in these it shows a remarkable tendency to concentration. Clarke gives an estimate, based on 246 determinations, of .05 per cent. Cr_2O_3 , but this must evidently be regarded as an average rather for the basic rocks than for the igneous group generally. Besides its occurrence in chromite and picotite, chromium enters into the constitution of some augites ("chrome-diopside") and olivines, as well as certain varieties of garnet.

Manganese occurs in very similar quantities in rocks of all classes, especially in the ferro-magnesian minerals. It rarely exceeds .3 per cent. as MnO . Washington and Hillebrand consider higher figures as generally due to error.

Nickel occurs in olivine and serpentine, also to a less extent in hornblende and biotite, as well as pyrites and pyrrhotine. The oxide rarely makes more than .1 per cent. of a rock, and the average is about .03. An interesting feature is its occurrence alloyed with the iron of meteorites. It is particularly abundant in the most basic rocks.

Cobalt is always less in amount than nickel, and rarely occurs in more than "traces." It is, however, less constantly associated with the basic group of rocks.

Barium and *Strontium* are almost always to be detected if looked for in analysing rocks. Together they usually amount to less than .1 per cent., but are sometimes more abundant. They occur in the feldspars, especially orthoclase and microcline. Barium is almost without exception present in greater quantity than strontium, and the latter seldom gives more than "traces."

Sulphur is almost invariably present in rocks, though always in small amount. It exists as pyrites or pyrrhotine: as an original constituent of igneous rocks it no doubt generally takes the latter form, accompanied at times by sulphides of copper, nickel, zinc, lead, and

other metals. Häüyne and nosean also contain sulphur.

Phosphorus.—This element is so uniformly distributed through the various rock types that Clarke's figure of .26 per cent. of P_2O_5 for the igneous rocks may be accepted as a close approximation. It occurs as apatite, and much more rarely as monazite.

Chlorine occurs almost entirely as a minor constituent of apatite (chlor-apatite). It is also found in scapolite and sodalite. That derived from rock-weathering has become concentrated as salt in the ocean, though how there comes to be enough for all the sodium therein to occur as chloride is not yet fully explained.

Fluorine, like chlorine, is primarily contained in apatite (fluor-apatite). It also occurs in tourmaline, topaz, and in many micas, while Penfield and Stanley have recently shown that it occurs in amounts up to 2.76 per cent. in various specimens of hornblende.*

Boron.—This substance appears among the rock-formers only in tourmaline in determinable quantities. It occurs as borax, etc., in the saline lakes of Italy, Thibet, and California.

Lithium.—This metal is closely allied to potassium and sodium, and their compounds usually contain small quantities of it. It also occurs more abundantly in lepidolite and other micas, in spodumene, and certain varieties of tourmaline.

Cerium and other metals of the "rare earths" occur among the igneous rocks in the sometimes abundant accessory orthite, or allanite, and less commonly in monazite. These minerals are responsible for a wide distribution of thorium, and may also contain uranium.

Heavy Metals, etc.—When sufficiently large quantities of material are taken for examination, all rocks afford traces of the ordinary commercial metals like tin, lead, zinc, antimony, copper, etc., and even of gold and silver. Several granites from California have been shewn to contain over 100 mg. of gold and up to $7\frac{1}{2}$ grammes of silver, while a Nevada granite showed over 1 gramme of gold and $5\frac{1}{2}$ grammes of silver per ton. Similarly it has been found that the andesites of Waihi, New Zealand,

* *Am. Journ. Sci.*, vol. xxiii. 1907, p. 23.

contain $1\frac{1}{2}$ grains of gold per ton and considerably more silver.* Such facts have a most important bearing on the origin of ore-deposits.† A single cubic mile of the andesite mentioned would contain $22\frac{1}{2}$ million ounces of fine gold. It is easy, therefore, to see that no very advanced stage of leaching by percolating water would be required for the formation of a workable lode wherever a suitable precipitant was met with along a channel of easy circulation. The frequent association of ore bodies with igneous rocks has often been discussed. The significance of the fact has, however, been much misunderstood. It can scarcely be argued that the igneous rocks are specially rich in the metals, for the sediments can only derive their material from the igneous group, and must therefore necessarily contain, on the average, exactly the same constituents. Where igneous intrusions cut the sediments, however, they raise the temperature of the circulating water, which increases its powers of solution, and the impediments they place in the way of circulation also make their contacts especially favourable places for ore deposition after the contraction consequent on cooling has produced cavities near their margins. Petrological methods find one of their most interesting applications in the study of ore deposits.

* Park, *Mining Geology*, London, 1907.

† See discussion in the *Miners' Guide*, pp. 12-31.

CHAPTER XX.

Radio-activity and the Rocks.

THE remarkable facts of radio-activity have recently been called upon to assist in elucidating many scientific problems, and amongst these are some of great interest for geologists generally and petrologists in particular. The influence of these new points of view is likely to be so far-reaching that some discussion of the matter can scarcely be omitted. It is obviously beyond the scope of this work to deal in detail with the theories of radio-activity, but it is necessary for the proper presentation of the subject to review some of the points in the development of modern ideas concerning it.

Radio-activity.—In order to render the effects of the “X-rays” visible to the unaided eye, it is necessary to employ a fluorescent screen, which is merely a piece of card coated with a suitable salt. Some of the salts employed for the purpose are strongly phosphorescent, that is to say, will go on emitting light if placed in a dark room, provided they have been previously placed in the sun. It occurred to Becquerel to try whether these phosphorescent substances were not capable of affecting a photographic plate without the aid of X-rays. He selected a salt of uranium, and soon found that his phosphorescent preparation did, in fact, darken a photographic plate as the X-rays do, even through paper, or thin sheets of certain metals. It so happened that on one occasion the uranium salt, without having previously been rendered phosphorescent, was left on a plate in a dark drawer for several weeks, and M. Becquerel thought it would be interesting to see if any effect had been produced. He ascertained, on developing the plate, that it had been darkened, and further experiments showed that neither sunlight nor phosphorescence had anything to do with the phenomenon. It was obviously inherent in the uranium preparation, and all compounds of uranium were found to give similar results.

The Discovery of Radium.—Shortly after Becquerel's fundamental discovery of the radio-activity of uranium, Schmidt found that the element thorium possessed similar powers. Then M. and Mme. Curie ascertained that various uranium-bearing minerals were more strongly radio-active than pure uranium itself. Pitchblende, the commonest natural source of uranium, was especially remarkable in this respect. It accordingly appeared that its activity must be due to something besides uranium, and after a series of most painstaking researches, these two physicists succeeded in demonstrating that pitchblende contained two new substances, which they named polonium and radium, far more powerful than uranium, but only existing in minute quantities.

The Origin of Radium.—It soon began to be perceived that though radium is a definite chemical element, it stands in some very close relationship to uranium. The different minerals which contained uranium, and those only, contained radium, and moreover the latter even appeared to be present in amounts strictly proportional to the quantity of uranium—one part, in fact, to something like 3,000,000 of the latter. This proportion has since been shewn to be variable, but the fact does not disturb the conclusions which it originally suggested. It was found, too, that radium itself gave off the rare gas called helium, in perceptible amounts within comparatively brief periods of time. Gradually the conclusion became forced upon physicists that radium was formed only to decay, and that it owed its radio-activity to the extraordinary energy developed in the process of change. But if it decays, a time ought obviously to come when there should be no more radium left, for instance, in a particular sample of pitchblende. Its constant presence therefore shows that there must be some process at work which makes good the decay, and there is no escape from the conclusion that radium is being continuously generated from uranium. This involves a process of atomic disintegration, an actual change or transmutation of one element into another, and the view that this is the case has been developed and established chiefly by the work of Rutherford and Soddy. Recent research shows that the change takes place in several stages, but it is none

the less certain that it is really going on. There is no means of controlling or starting, or stopping the process, but we can actually watch it progressing under our eyes. Uranium can be traced, through various stages of change, into radium, giving off helium at the same time, and similarly radium, it is believed, changes into the familiar metal lead, also giving off helium in the process.

The Energy of Radium.—For our present purpose it is unnecessary to discuss the remarkable speculations which have followed from the discovery of radium and its allies. We have chiefly to concern ourselves with the enormous stores of energy which radio-active substances possess. How important these are is made clear from the fact that the complete disintegration of a given amount of radium produces about two million times as much energy as would be done by burning the same quantity of coal. One pound of radium contains a store of energy equal to that generated by burning 1,000 tons of coal. This energy, however, is not emitted so rapidly as that produced in burning coal. In fact, it takes nearly 2,000 years for half the energy in any stated amount of radium to be given off, and a similar period for half that in the remainder, while no means of either stopping or accelerating the process has been discovered. It might be thought that such slow rates of change would scarcely give perceptible indications of their progress. But such is far from being the case. A radium salt always maintains itself at a temperature several degrees higher than that of the surrounding atmosphere, whatever that may be. And when we come to examine the rocks, we are faced by a still more remarkable state of affairs.

Underground Temperature and Geological Time.—For many years it has been a matter of observation that at a comparatively few feet below the surface of the earth, the temperature is quite unaffected by summer heat or winter cold. On the other hand, we find, as we descend further, that the temperature always rises, commonly at the rate of about 1° Fahr. for each 60 feet of descent, or 1° Cent. for each 100 feet. On the assumption that the earth is a cooling body, and is every year losing a part of the heat it originally had as a molten mass, it is possible to calculate the time that has elapsed since it has become

cool enough to allow water to settle on its surface, and sedimentary rocks to accumulate. The matter simply depends on the conductivity of the rocks of which the earth is composed. Lord Kelvin made such a calculation, and announced as a result that the time since sedimentary rocks began to form on the earth could not be greater than 40,000,000 years. Professor Tait, in 1876, was still more emphatic. These are his words: "We can say at once to geologists, that, granting this premiss—that physical laws have remained as they now are and that we know of all the physical laws which have been operating during that time—we cannot give more scope for their speculations than about ten, or say at most fifteen millions of years." And referring to those who, like Darwin and Lyell, pointed out that this period was altogether insufficient for the accumulation of the known sediments, he goes on: "So much the worse for geology as at present understood by its chief authorities, for . . . physical considerations . . . render it utterly impossible that more than ten or fifteen millions of years can be granted."

Radio-activity and Underground Temperatures.—It will be noted that Professor Tait made a reservation in his somewhat sweeping statement, quoted above, which has become very significant during the last few years. He assumes that "we know of all the physical laws which have been operating." That is just what we did *not* know at the time he wrote. At first it looked as if radio-activity could have little connection with the internal heat of the earth, and it was soon proved that it cannot account for the heat of the sun. But Strutt's researches on rocks of all descriptions speedily shewed what an important factor it may be in terrestrial physics. It is estimated that the quantity of radium in the rocks of the earth's crust is only about one ounce in 6,000,000 cubic miles, yet the amount of heat which this apparently infinitesimal proportion would give out is actually very much *more than enough* to keep up the temperature of the earth, if uniformly distributed. It is, in fact, quite evident that there must be a considerable concentration of radium near the surface of the earth, and that the exposed rocks contain considerably more than those buried at a depth.

It is by no means necessary, as might at first be supposed, to abandon the old conception of the earth as a cooling globe. The very discovery of radio-activity should warn us that we may still be far from understanding all the laws of physics, and we must not run to extremes in applying our newly won knowledge. At the same time there can be no doubt that the effects of radio-activity must be allowed for in attacking the problem of underground temperatures, and not only prolong the period, both past and future, which we may assign to the operation on the earth of conditions similar to those of the present day, but compel us to admit another among the factors which may determine the formation of igneous magmas.

Radio-activity of the Rocks.—We owe to the investigations of Strutt, Joly and others, a considerable amount of information regarding the radio-activity of various rocks.* There is a slight discordance in the numerical results, and as this makes the figures not strictly comparable none are quoted here. From a relative point of view, however, they indicate that among the igneous rocks, acid types are considerably more radio-active than basic ones, and also apparently that plutonic types are more so than lavas or dyke rocks. In general the sediments are rather less active than the igneous rocks, but no definite relation appears between their lithological character and their degree of radio-activity. It seems, however, that the modern deep-sea deposits are particularly rich in radio-active constituents especially radiolarian ooze and the abyssal "red clay."

Pleochroic Halos.—Of special interest to petrologists is the fact that in ordinary sections there is direct evidence of the presence of radio-active substances in the shape of the well-known "pleochroic halos" that may be seen surrounding minute crystals and grains of certain minerals, notably zircon and orthite. Nothing is known as to the precise nature of the change which takes place in the enclosing mineral and thus gives rise to the halo, but that it is due to the effects of radio-active processes is now well ascertained. The following minerals are found to show halos, though it must be stated that in some of

* Strutt *Proc. Roy. Soc. A* (1906), p. 472; Joly, *Radio-activity and Geology*, p. 37, etc.

them the phenomenon is very rare: biotite, augite, hornblende, muscovite, chlorite, tourmaline, cordierite, staurolite, and andalusite. Of the minerals producing halos, the following have come under the writer's notice: zircon, sphene, apatite, orthite (allanite), and epidote. As far as the rocks are concerned, halos are far more common in those of igneous origin than in the other classes, and are especially noticeable in the plutonic types, particularly the granites. It may be noted that even zircon, round which halos are most frequently met with, may occur enclosed in such a susceptible mineral as biotite without the slightest trace of any halo being seen. However, a halo round zircon is certainly the normal state of affairs, and the same may be said of orthite. It is curious to notice that large crystals of these minerals may fail to give rise to halos, though these last may be conspicuous round the smaller crystals in the same slice. Round apatite and epidote halos are only occasionally seen, and are usually faint, while round sphene they are extremely rare.

Shape and Size of Halos.—It is evident that, if three dimensions are considered, halos are usually spherical, and thus give circular sections, except in cases where the enclosed crystal is distinctly elongated and of sufficient size for the difference of length and breadth to be appreciable. In the case of large irregular grains or granular aggregates the halo may be quite irregular in shape, but extends to a uniform distance from each part of the margin of the substance which it surrounds. Another feature revealed by measurement is the very slight variation in the size of different halos. A series of approximate measurements, made by means of an eyepiece micrometer, of the breadths of fairly well-marked halos seen round various distinctly visible minerals in a variety of rocks illustrates this point and serves to shew that there is no apparent relation between the small variations that are noticed and the minerals concerned.* Roughly speaking, all ordinary halos are between .03 and .04 mm. in breadth. It appears, however, that even these minute differences can be accounted for, and that halos due to radium are

* Mennell, *Geol. Mag.*, Jan., 1910, pp. 16-17.

about $\cdot 032$ or $\cdot 033$ mm. in breadth, while thorium halos are about $\cdot 039$ or $\cdot 040$ mm.

Various Features.—The more intense halos are usually uniform in tint from inside to outside, or slightly lighter towards the outer edge. Irregularities in distribution are, however, fairly frequent, and the halos are sometimes dark and light in uneven patches. This is probably due in most cases to the radio-active substance being present merely as inclusions in the interior of the mineral to which the halo appeared due. This is the more probable as such minerals as apatite and sphene cannot be radio-active in virtue of their normal constituents, or even their usual impurities. Epidote, too, may owe its occasional activity to minute inclusions of orthite. As bearing on this point, may be noted a granite from the Zimbabwe Ruins in Rhodesia, which contains apparently primary epidote enclosed in biotite. The epidote in turn encloses irregular patches of orthite, and wherever the latter approaches within $\cdot 039$ mm. of the edge of the epidote, the biotite within that limit shows the usual darkening. In a few cases—always, apparently, round rather large inclusions—the halos may have a rim darker than the interior. Thus, in the granite to the north of Kahlele's Kraal, in the Matopo Hills, and in that east of the Nanatali Ruins, in the Insiza district of Rhodesia, there are well-marked halos round good-sized orthite crystals enclosed in biotite. These halos are usually very sharply defined on the outside, and have the margins distinctly darker than the parts nearer the orthite. A similar feature may be noticed round some of the zircons in a biotite granulite from the neighbourhood of Rhodes' Drift on the Limpopo River, Rhodesia. It is also well seen round the larger zircons in the well-known cordierite granulite of the Bodenmais, Bavaria.

Halos are rather rare in tourmaline, though noticed long ago by Michel Lévy.* That this mineral does not readily lend itself to their formation in it is obvious from the evidence of such rocks as the Cape Town granite. My slides of specimens from near the contact show several instances of small zircons at the junction of biotite flakes

* See *Minéraux des Roches*, p. 288.

and tourmaline crystals, and whereas the biotite shows a semi-circle of intense pleochroism, the halos are incomplete, owing to the tourmaline being entirely unaffected. The same fact was noted at several junctions of biotite and cordierite, though in one case a good example of a composite halo, half in biotite and half in cordierite, was observed. Several fairly distinct halos were also seen round zircons entirely enclosed in tourmaline, and we may perhaps infer that in these particular cases the enclosures were more strongly radio-active than usual. It is noticeable that where the cordierite of this rock has been altered into the so-called "pinite" pseudomorphs, the halos are much more intense than in the fresh cordierite itself. Halos in hornblende are rather rare, though this is perhaps due partly to the much greater scarcity of inclusions than in biotite, which seems always to have crystallised by preference on a nucleus of previously formed accessory minerals. In contrast to tourmaline and hornblende, it is remarkable to find halos well shown in such minerals as augite and muscovite, which are not normally pleochroic. It is also an interesting point that halos never seem to occur in minerals capable of causing them. Thus there are none round the inclusions of zircon in the large orthite crystals of the Jibuyi River granite in North-Western Rhodesia, nor does the epidote of the same rock show any where it encloses orthite crystals, a feature which may also be noticed in numerous other Rhodesian granites, e.g. those of the Matopos, Kalomo, and the Zimbabwe Ruins.

Helium and the Age of the Rocks.—The helium which is produced during the decay of radium, is found to accumulate in the parent mineral, and the same is the case with that produced from the "primary" radio-active elements thorium and uranium. It is evident, therefore, provided that no important disturbing features have to be taken into account, that the amount of helium present is proportionate to the time which has elapsed since the original deposition of the mineral. There are several means of reckoning up how much is formed in a year, and from the total amount present a simple arithmetical calculation should give the age of the containing substance. If, therefore, we have had to abandon the old physical method

of estimating geological time, it seems possible that we may be placed in possession of a much more accurate one. The practical difficulties in the application of the method are very great, and it is easy to criticise the results obtained by Strutt,* and others since. The obstacles do not, however, appear to be insuperable, and we thus have grounds for hoping one day to be able to state the age of particular geological formations, not in the merely relative terms of nineteenth century geology, but in actual periods of years.

* On the Accumulation of Helium in Geological Time, *Proc. Roy. Soc. A.*, vol. 81 (1908), pp. 272-277.

CHAPTER XXI.

Collection and Preparation of Material.

FOR the collection of specimens there is only one really necessary implement, namely, a good hammer, though a chisel is sometimes of service. The hammer-head should be mounted on a handle which is unlikely to break when used on a tough rock, and in such a way that it is perfectly firm and not liable to work loose when in use. The only way to secure this, at any rate in dry countries, is to wedge the head tight by means of cross wedges at right angles to one another, which are glued in position. The writer has used such a hammer in the tropics for over a year before the head became loose, and this in spite of working amongst the most intractable igneous and metamorphic rocks. If the head is not secure the handle is liable to break off short at any moment.

With regard to weight considerable misconception seems to prevail. A pound and a half is heavy enough for dealing with any kind of rock, in fact, it may be safely asserted that rocks not readily breakable with properly used hammers of that weight do not exist. The point of attack should be a place where the outcrop shows an edge with a fairly sharp angle. The blow struck should be hard, and care should be taken that the blows all fall on the same spot, when several are required. It is only when large boulders of a tough rock have to be broken that a heavier hammer is required.

As to size, the collector will of course be guided by the eventual destination of the specimen. Those for museums and similar institutions should be of a uniform size like 5 by 4 inches, large enough to give a good idea of the characters of even a coarse-grained rock. On the other hand, the student or amateur will probably find that limitations of space prevent his specimens being larger than about 3 by 2, or $2\frac{1}{2}$ by $1\frac{1}{2}$ inches, except, perhaps, in the case of specially interesting or very coarse-grained types. In the case of museum specimens, when a machine

is available for the purpose, trimming should be left to be done at the institution itself, a piece of the rock being selected which is rather larger than the standard size. The student, however, will find it advantageous to do his trimming in the field, so that in case of accidental fracture, another specimen can be secured.

In all cases the freshest part of the rock should be chosen, and specimens should always be broken from the rock *in situ* unless this is difficult to manage and there can be absolutely no question as to the identity of the fragments which may be lying about. In England and

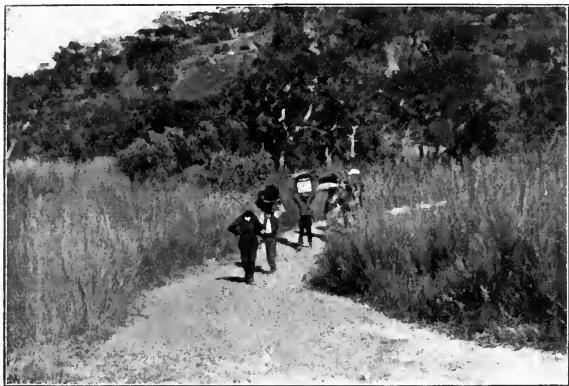


FIG. 123.—ON A COLLECTING TRIP IN RHODESIA.

other settled countries, quarries and artificial exposures, of every description give excellent opportunities for securing good specimens, but in newer countries, where artificial sections are rarely or never to be seen, the hardest portion of the outcrop must be selected for attack, In even the most hopeless looking exposures comparatively fresh specimens are usually to be found by careful search ; thus the centres of spheroids are often quite undecomposed although the exteriors are very far gone, and even the most advanced alteration may be scarcely more than skin deep.

Where a rock-cutting machine is in use, slices for making microscope slides can be cut direct from the hand specimens. In other cases, the collector will find it necessary to provide himself with an additional fragment for the purpose. This may be a chip, if the collector prepares his own slides, or a piece about an inch cube, if it is to be sent to Germany or elsewhere for slicing. In cases where transport is a difficulty, as on exploring expeditions, and in newly opened-up country, pieces about $1\frac{1}{2}$ by 1 by 1 inch are usually large enough for a slice to be cut and sufficient left over to give an idea of the general character of the rock. Numbered canvas bags are very useful for carrying about specimens when travelling, a separate one being used for the samples from each particular locality. Records of their mode of occurrence, field relations, etc., should be kept in a note-book, and each fragment should be wrapped in a separate piece of paper with its reference number written on it in large figures in more than one place.

The preparation of rock sections involves so much tedious labour and takes up such an amount of time, that where expense is not the first consideration the geologist will generally find it better to get his slides made for him than to make them himself. If the samples are sent to Germany for slicing, they should be expressly ordered to be on the standard English 3 by 1 inch glass slip, as this is much more convenient than the continental size. The geologist will, however, find that, with a little practice, it is easy to prepare slices equal to those of the German dealers. During the past ten years the writer has made nearly a thousand slides with his own hands, so that he can speak with some confidence on this point. The great thing is not to be satisfied with anything that is only fairly good. Medium grained dolerites may be recommended as perhaps the most suitable rocks for practice.

The first essential is to procure a convenient piece of rock for grinding. This may be done, either by chipping off as thin a piece as possible of the right size, about that of a shilling, or by cutting it off with a machine. The latter consists essentially of a steel disc, rotated by hand, foot, or mechanical power, and armed with diamond dust,

which really does the cutting. The rock is fixed in a clamp and made to press against the disc by means of a weight. To use the machine, some diamond is finely powdered in a small steel mortar arranged so that the pestle fits in accurately, and permits none of the powder to escape. The latter is mixed with a little oil or soapy water, and applied to the edge of the disc with the tip of the finger, being well rubbed in by means of a smooth piece of agate. This process is known as "arming" the wheel, and one arming is sufficient for cutting a considerable number of slices if due care is taken. Soapy water is placed in the receptacle provided for the purpose, its aim being to lubricate the wheel while the cut is being made. Should the supply fail, and the disc be permitted to become dry, the diamond will be immediately stripped off its edge.

In starting the wheel, care must be taken to apply it to as even a surface of the rock as possible, since sharp edges are apt to strip off the diamond dust during the first few revolutions, before it has time to bite. The lubricant must flow freely, but not too freely, though in the case of limestones, serpentines, etc., the cut readily becomes clogged unless a good flow is maintained. About five minutes will suffice, when the machine is running smoothly, to cut off a piece of rock of the right size for preparing a slide. It is usual to make a preliminary cut to secure a plane upper face, or a smooth surface may be produced by grinding on an emery or carborundum wheel. A cut is then made from $\frac{1}{32}$ to $\frac{1}{16}$ of an inch lower down, according to the strength of the rock, so that a slice of that thickness is obtained having both sides smooth.

It is then necessary to polish one of the faces of the slice. If they differ in size, the larger is selected and ground smooth by rubbing with flour emery or carborundum on a sheet of plate-glass. In the case of pieces chipped off a rock specimen, it will first be essential to produce a flat surface by grinding with coarse emery (40 or 60 mesh), on an iron or gun-metal plate, after which it is finished off as above, after carefully washing free from all traces of the coarse emery. After again washing, the slice is ready for attaching to a piece of glass, which is intended to serve as a kind of handle while the specimen is being reduced

to the proper thinness. This attachment is a very important process, and on its proper performance the success of the whole operation depends. Canada balsam is the medium used for the purpose. A drop or so is laid on a square of plate glass about $1\frac{1}{4}$ or $1\frac{1}{2}$ inch across, and is then heated until of the proper consistency, which is reached when a thread, drawn out between the points of a pair of forceps, is found to be brittle, so that it breaks instead of bending, when pressed by the finger, or when the forceps are closed. The toughness of the balsam, and consequently the thinness to which a slice can be reduced without risk, is greatly increased by the addition of a little shellac. This may be conveniently done by laying a flake of that substance on top of the balsam prior to heating it, afterwards stirring with the point of a mounted needle if necessary to secure perfect mixing.* The right point having been reached, the piece of rock, which should have been heated at the same time as the balsam, is carefully laid on the latter and pressed down, care being taken to exclude air bubbles. The glass, with the slice attached, is then allowed to cool, a 2 oz. weight or similar object being placed upon it. When quite cold it is ready for grinding, which is carried out with 60 mesh emery powder. Having been reduced as thin as is safe by this method, before all the balsam round the edges has disappeared, the coarse emery is washed off, and the grinding finished as before, with flour emery, on the glass plate. Great care is necessary in the final stages to avoid entirely removing the slice from the glass. In the case of extremely fine-grained rocks the thinness is reduced to the furthest possible limit, but in most rocks about .03 mm. or $\frac{1}{1000}$ inch is the standard thickness. Its attainment may be recognised from the quartz or felspar, which are present in nearly every rock, showing only greys of the first order when examined in polarised light.

It is now necessary to mount the object for permanent preservation. It is first of all well washed to get rid of every trace of emery, and then the superfluous balsam is

* Do not try to economise the balsam, and always use more than is absolutely necessary, as it protects the edges of the slice from being torn by any large grains of emery which may have got accidentally on to the fine emery plate.

scraped off with the point of a hot knife, or removed by means of benzole, alcohol or turpentine. A little fresh balsam is then placed on the section, and the whole gradually heated. When the section is loosened by the melting of the balsam underneath, it is made to slide off by means of a mounted needle, every precaution being taken to prevent breakages, and a track of balsam being formed for it to slide easily over. It is thus transferred on to a clean 3 in. by 1 in. glass slip, on which a few drops of balsam have been heating. A cover glass of suitable size is then thoroughly cleaned with soft wash leather and placed on the section, air bubbles being got rid of by carefully moving it about with the point of the needle

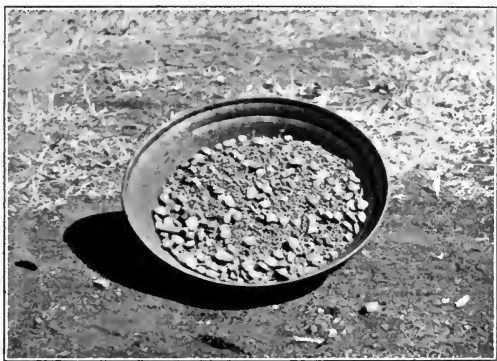


FIG. 124.—PROSPECTING PAN, FILLED WITH GRAVEL.

if necessary. The slip is then removed from the heating table, and the cover pressed down firmly, so as to squeeze out superfluous balsam. When cool, as much as possible of the latter is removed by means of a warm knife, after which the remainder is washed off with alcohol or turpentine. The slide is then ready for labelling, after proper examination under the microscope in the case of unidentified rocks.

Fragmentary materials naturally require a somewhat different treatment. Sands may often be mounted direct,

after separating most of the quartz by washing off the lighter materials with a current of water or some process of panning, and afterwards sieving to obtain particles of sufficiently uniform size. The ordinary prospecting "pan" or "dish" used by miners is extremely useful for concentrating the heavier minerals from large quantities of sand or pulverised rock, and the study of the residues is one of considerable interest. To avoid air bubbles, when mounting, the powder may be laid on a glass slip and carefully moistened with turpentine; then covered with balsam and mounted in the usual way. A glass rim or "cell" is useful to surround such objects, but may be dispensed with when the powder is very fine. Another method of mounting is to distribute the grains evenly over a film of hard balsam, which is then slightly warmed to make them adhere. A glass cell is then placed round the objects, filled with balsam dissolved in benzole, and a cover placed on top. When grinding is necessary, the grains are first stuck down on to a thin plate of mica, which is in turn stuck on to glass, Canada balsam being employed for the purpose as usual. When the grinding of one side is complete, the grains can then all be turned over together by cleaving off the mica with them attached, reversing it on to a new glass plate, and stripping off the rest of it when the grains have been secured.

Each slide should be carefully labelled after examination under the microscope, and then put away in a safe place. For purposes of storage a small cabinet, in which the slides are laid flat so that the labels are all visible, is the best. The provision of spaces for writing the names opposite to numbers corresponding to the slides in no way makes up for the labels being invisible, as such a system renders it very troublesome to make changes in the arrangement, while elasticity in such matters is absolutely indispensable.

THE END

Index of Subjects

ACCESSORY minerals, 64, 100
 Acid igneous rocks, the, 118
 Acmite, 57
 Actinolite, 55
 Adularia, 39
 Aegirine, 59
 Age of the earth, 237
 Agglomerate, 182
 Akerite, 147
 Albite, 41
 Allanite, *see* Orthite
 Allivalite, 167
 Allotriomorphic minerals, 88
 Almandine, 78
 Alnoite, 170
 Alteration of rocks, 218
 Aluminium, 229
 Aluminous silicates, 38
 Amblystegite, 59
 Amphiboles, 54, 60
 Amphibolites, 194, 214
 Amygdaloidal rocks, 100
 Analcime, 80
 Analyser, 17
 Andalusite, 48, 50
 Andesine, 43
 Andesite, 86, 148
 Anorthite, 41
 Anorthoclase, 41
 Anthophyllite, 56
 Antimony, 233
 Apatite, 64
 Aplite, 121, 127
 Apophyllite, 80
 Archæan rocks, 203

Arkose, 175
 Augite, 58
 Average composition of rocks,
 104, 226
 BANDED ironstones, 192, 224
 Barium, 232
 Barytes, 74
 Basalt, 86, 159
 ,, melilite, 172
 Basic igneous rocks, 150
 Basic patches in granite, 121
 Bastite, 71
 Bathyliths, 85
 Bauxite, 178
 Bertrand Lens, 22
 Beryl, 68
 Biaxial minerals, 17, 23, 27
 Biotite, 53
 Bisectrix, 23
 Blue-ground, *see* Kimberlite
 Borolanite, 156
 Boron, 233
 Breccia, 174, 191
 Brewsterite, 80
 Bronzite, 59
 Bytownite, 43
 CALCITE, 75
 Calcium, 229
 Carbon, 28, 231
 Cassiterite, 35
 Cementation, 192
 Cerium, 233
 Chabazite, 80

- Chalcedony, 31
 Chalk, 179
 Charnockite, 125
 Chemical composition of rocks, 225
 " reactions of minerals, 3
 Chert, 180
 Chiastolite, 49
 Chlorine, 233
 Chlorite, 72
 Chloritoid, 73
 Chromite, 33
 Chondritic structure, 173
 Circulation of material, 107
 Classification of igneous rocks, 81
 Clastic rocks, 174
 Clay, 177
 Cleavage, 6
 " slaty, 189
 Clinocllore, 72
 Coal, 182
 Cobalt, 232
 Coccoliths, 179
 Collection of material, 244
 Colour, of minerals, 9
 Columbite, 157
 Comagmatic regions, 101
 Compensation, 26
 Conglomerates, 174
 Contact metamorphism, 195
 Copper, 225
 Copper pyrites, 69
 Cordier, petrographical work of, 82
 Cordierite, 67
 Corrosion of crystals, 95
 Corundum, 31
 Crocidolite, 55
 Cross hatching, 22
 Crush breccias and conglomerates, 191
 Crystalline forms, table of, 6
 Crystallites, 8
 Crystallization, order of, 90
 " stages of, 94
 DECOMPOSITION of rocks, 218
 Dedolomitization, 108
 Density of minerals, 1
 Devitrification, 98
 Diabase, *see* Dolerite
 Diallage, 58
 Diamond, 28
 Diatomaceous earth, 181
 Differentiation, 101
 Diffusion column, 11
 Diopside, 58
 Diorite, 86, 144, 216
 Disintegration of rocks, 218
 Dispersion, 25
 Ditroite, 118
 Dolerite, 86, 154
 Dolomite, 76, 180, 222
 Double refraction, 16
 " " anomalous, 20
 Dykes, 84
 EARTH'S INTERIOR, 116
 Eclogite, 202
 Elaeolite, 45
 Elements, 28, 225
 Emery, 32
 Enstatite, 59
 Epeirogenic movements, 204
 Epidiorite, 158, 194, 205, 208, 212
 Epidosite, 194, 221, 222
 Epidote, 66, 73
 Eutectics, 92
 Extinction, 17
 Extraordinary ray, 16
 FAYALITE, 61
 Felsite, *see* rhyolite, etc.
 Felspars, 38
 Felspathoids, 44
 Fibrolite, 50
 Fissure eruption, 112
 Flint, 179, 180
 Flow structure, 99
 Fluor, 71
 Fluorine, 233
 Foliation, 190, 193 and fig. 98
 Forsterite, 61
 Fragmental rocks, 174

- Fragmentary materials, mounting of, 249
- Fundamental complex, 204
- GABBROS, 86, 150
- Gahnite, 33
- Garnet, 77
- Gedrite, 57
- Generations of crystals, 95
- Girvanella, 179, 181
- Glassy rocks, 88, 97
- Glauconite, 175
- Glaucophane, 55
- Globigerina ooze, 179
- Glomero-porphyrritic structure, 95
- Gneiss, 194, 207
- Gold, 233
- Granite, 86, 121
- Granitic texture, 89
- Granodiorite, 125
- Granophyre, 86, 127
- Granulite, 194, 209
- Graphic structure, 93
- Graphite, 28
- Gravels, 174
- Greensands, 175
- Greisen, 121
- Greywacks, 175
- Grits, 175
- Grossular, 77, 78
- Groundmass, 95, 98
- Gypsum, 75
 - „ plate, 25
- HÆMATITE, 32
- Halos, pleochroic, 54
- Hammer, the collector's, 244
- Harmotome, 80
- Haüyne, 46
- Heavy liquids, 1
- Heavy metals, 233
- Helium, 237, 242
- Heulandite, 80
- Holocrystalline rocks, 88
- Hornblende, 55
- Hyalosiderite, 61
- Hybrid rocks, 108
- Hydrogen, 230
- Hypabyssal rocks, 85
- Hypersthene, 59
- IDIOMORPHIC minerals, 88
- Idocrase, 79
- Igneous rocks, composition of, 81, 104, 227
 - „ classification of, 83
 - „ nomenclature of, 86
 - „ occurrence of, 84
 - „ origin of, 101
 - „ structure of, 88, 96
- Ijolite, 167
- Ilmenite, 36
- Injection, lit par lit, 188, 207
- Interference figures, 22
 - „ tints, 18
- Intermediate rocks, 136
- Internal heat of earth, 116
- Iron, 29, 229
- Ironstone, banded, 192
 - „ surface, *see* Laterite
- Isotropic minerals, 17, 27
- Itacolumite, 193
- JACUPIRANGITE, 167
- KAOLIN, 71
- Kimberlite, 28, 169
- Kyanite, 49
- LABRADORITE, 43
- Laccolites, 85
- Lamellar twining, 21
- Lapilli, 184
- Lapis Lazuli, 46
- Lapparent, on petrography, 82
- Laterite, 178, 220
- Laumontite, 80
- Laurvikite, 145
- Lavas, 84, 187, *see also* Basalt, etc.
- Lead, 233
- Lemniscates, 23
- Lepidolite, 52

- Leucite, 45
 Leucoxene, 36
 Limburgite, 86, 171
 Limestone, 179, 222
 Limonite, concretionary, *see*
 Laterite
 Liparite, *see* Rhyolite
 Liquefaction during refusion, 109
 Lithophyse, 132

 MAGMAS, 102, 196
 Magmatic water, 107, 198, 214
 Magnesium, 230
 Magnetic separation, 2
 Magnetite, 34
 Manganese, 232
 Marble, 201
 Melanite, 77, 78
 Melilite, 47
 Melting points, list of, 90 *note*
 Mesolite, 80
 Metamorphism, 186
 Metasomatism, 191
 Meteorites, 29, 173
 Methylene iodide, 1
 Mica, *see* muscovite, biotite, etc.
 ,, plate, 26
 Microcline, 40
 Microgranite, 127
 Micrographic structure, 93, 128
 Micropegmatite, 92, 128
 Microperthite, 40
 Mixed rocks, 188, 194, 209
 Mode, 87
 Molybdenum, 232
 Monmouthite, 168
 Mounting of specimens, 248
 Muscovite, 52
 Mylonite, 191

 NATROLITE, 80
 Negative crystals, 14
 Negative double refraction, 25
 Nepheline, 44
 Nickel, 232
 Nicol prisms, 17

 Nordmarkite, 141
 Norm, 87
 Norite, 153
 Nosean, 46

 OBSIDIAN, 132
 Oceanic deposits, 179
 Oligoclase, 43
 Olivine, 61
 Oolite, 179, 182
 Ooze, 179, 181
 Opal, 75
 Opaque minerals, 11
 Opicalcite, 202
 Ophitic structure, 97, 155
 Optical properties of minerals, 27
 Optic axis, 22
 Optic axial angle, 24
 Orbicular structure, 96
 Ordinary ray, 16
 Ore deposits, 234
 Orogenic movements, 204
 Orthite, 65
 ,, in biotite, 54
 Orthoclase, 39
 Orthophyre, 86, 140
 Ottrelite, *see* Chloritoid
 Oxides, 30
 Oxygen, 228

 PALAGONITE tuffs, 180
 Pectolite, 80
 Pegmatite, 121
 Pennine, 72
 Peridotite, *see* Picrite
 Perlitic structure, 97
 Perovskite, 66
 Perthite, 40
 Petrographical provinces, 101
 Phenocrysts, 95
 ,, composite, 95
 Phonolite, 143, 147, 149
 Phosphorescence, 235
 Phosphorus, 233
 Picotite, 33
 Picrite, 86, 166

Piedmontite, 74
 Pillow structure, 100
 Pinite, 67
 Pitchstone, 131, 134, 142
 Plagioclases, the, 41
 Pleochroic halos, 54, 239
 Pleochroism, 11
 Pleonaste, 33
 Plutonic rocks, 84, 86
 Pneumatolytic agencies, 200
 Pœcilitic structure, 89
 Polarised light, phenomena in, 16
 Polariser, 17
 Porphyrite, 86, 146
 Porphyritic structure, 95
 Porphyry, 129, 141
 Positive double refraction, 25
 Potassium, 230
 Prehnite, 80
 Primitive crust of the earth, 81
 Pseudoporphyrityc structure, 89
 Pumice, 132
 Pyrites, 89
 Pyrognomic minerals, 196
 Pyro-metamorphic rocks, 195
 Pyrope, 78
 Pyroxenes, the, 58
 Pyroxenite, 152, 165
 Pyrrhotine, 69

QUANTITATIVE classification, 87
 Quartz, 30
 „ wedge, 25
 Quartzite, 176, 200

RADIO-ACTIVITY, 235
 Radium, 236
 Refraction, double, 16
 Refractive index, 13, 15
 Refusion, 102
 Regional metamorphism, 203
 Relief of pressure, 197
 Resorption, 95
 Rhabdoliths, in chalk, 179
 Rhyolites, 86, 132
 Riebeckite, 55

Rock-cutting machine, 246
 Rutile, 34, 53, 177

 SAGENITE, 35
 Sands, 175, 249
 Sandstone, 175
 Sanidine, 39
 Sarsens, 176
 Scapolite, 47
 Schists, 190, 193
 Schorl rock, 131
 Scolecite, 80
 Sections, preparation of, 246
 Sedimentary rocks, 174
 Segregation, 102
 Selective absorption, 107
 Sericite, 52
 Serpentine, 71
 Serpentine rock, 202, 221
 Sequence of eruptions, 114
 Shales, 177
 Shales, metamorphism of, 211
 Shonkinite, 154
 Sign of double refraction, 25
 Silica, percentage of, in minerals, 4
 „ „ in rocks, 86
 Siliceous sinter, 182
 Silicon, 228
 Silver, 233
 Sinter, 182
 Skeleton-crystals, 9
 Slates, 177
 Slicing of rocks, 246
 Sodalite, 46
 Sodium, 230
 Sonstadt's solution, 2
 Sorby, work of, 82
 Specific gravity, determination
 of, 1
 Spessartine, 78
 Sphene, 65
 Spherulitic structure, 98, 128
 Spinel, 33
 Staurolite, 51
 Stilbite, 80
 Strontium, 232

- Sulphur, 232
 Syenites, 86, 139
 ,, nepheline, 157
 TACHYLITE, 87, *see also* Basalt, etc.
 Talc, 72
 Terrigenous deposits, 179
 Teschenite, 169
 Thermal metamorphism, 195
 Thorium, 233
 ,, halos, 241
 Thulite, 222
 Tin, 233
 Titanite, *see* Sphene
 Titanium, 231
 Toadstone, 155
 Tonalite, 125
 Topaz, 68
 Tourmaline, 70
 Trachyte, 86, 143
 Transfusion, 196
 Tremolite, 55
 Tridymite, 196
 Tufa, 180, 220
 Tuff, 182
 Twinning, 21
 ULTRABASIC igneous rocks, the,
 165
 Unakite, 222
 Underground temperatures, 237
 Uniaxial minerals, 17, 22, 27
 Uralite, 56
 Uranium, 233, 235
 VANADIUM, 231
 Vesicular rocks, 99
 Vesuvianite, *see* Idocrase
 Vitreous rocks, 88, 97
 Volcanic rocks, 84
 Vulcanicity, 112
 WATER, 230
 Weathering, 218
 Wollastonite, 78
 XENOLITH, 100
 ZEOLITES, the, 80
 Zinc, 233
 Zircon, 67
 ,, in biotite, 54
 Zirconium, 231
 Zirkel, 82
 Zoisite, 74
 Zones of the earth's crust, 187
 Zoning of crystals, 14

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